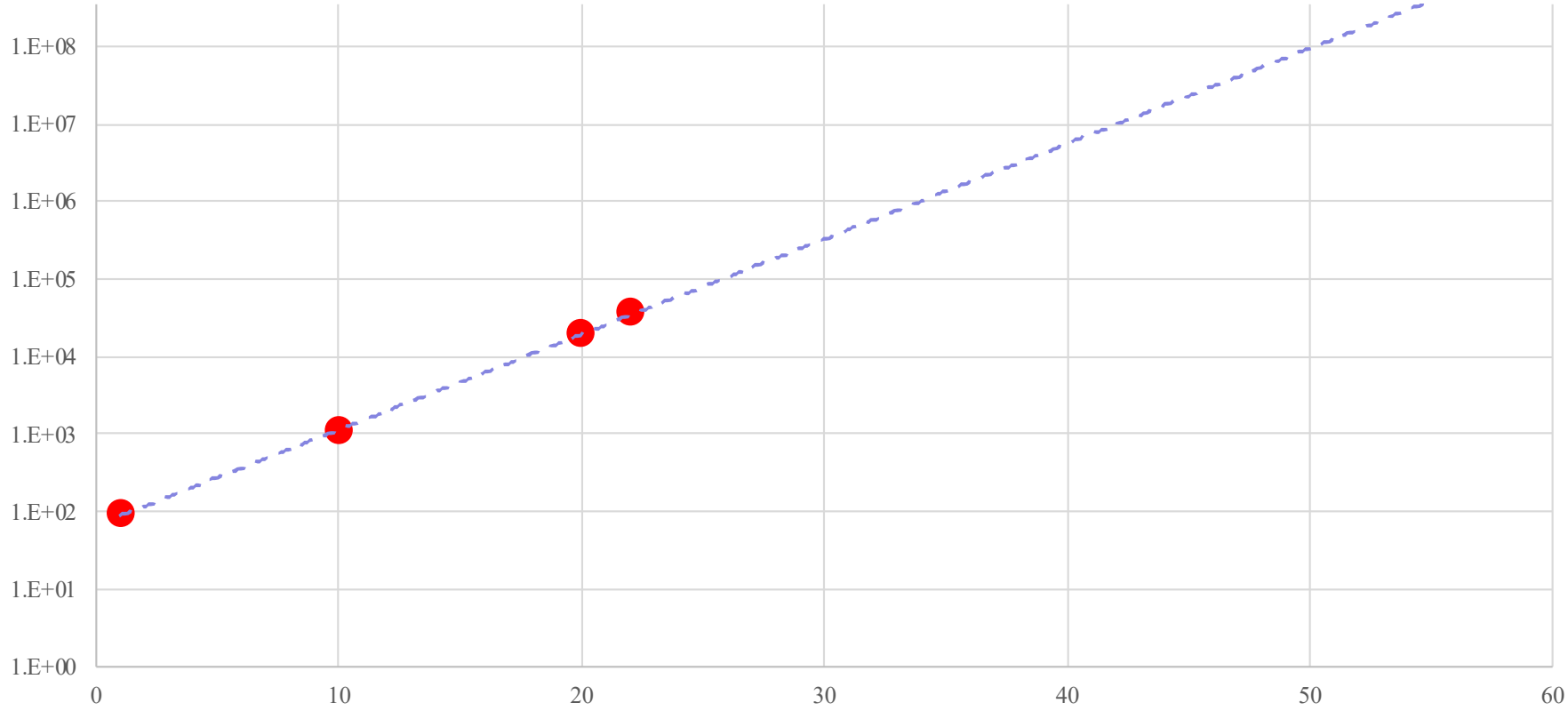
Studying Hot QCD with Jets

Sevil Salur

Cumulative Cases in USA

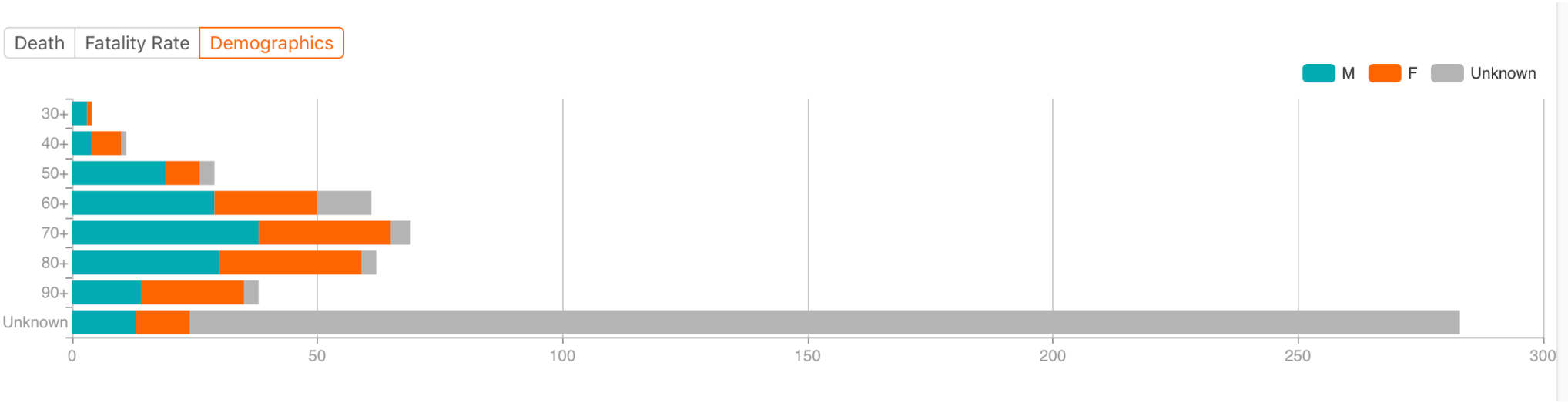
Data from https://coronavirus.1point3acres.com



Days since March 1st

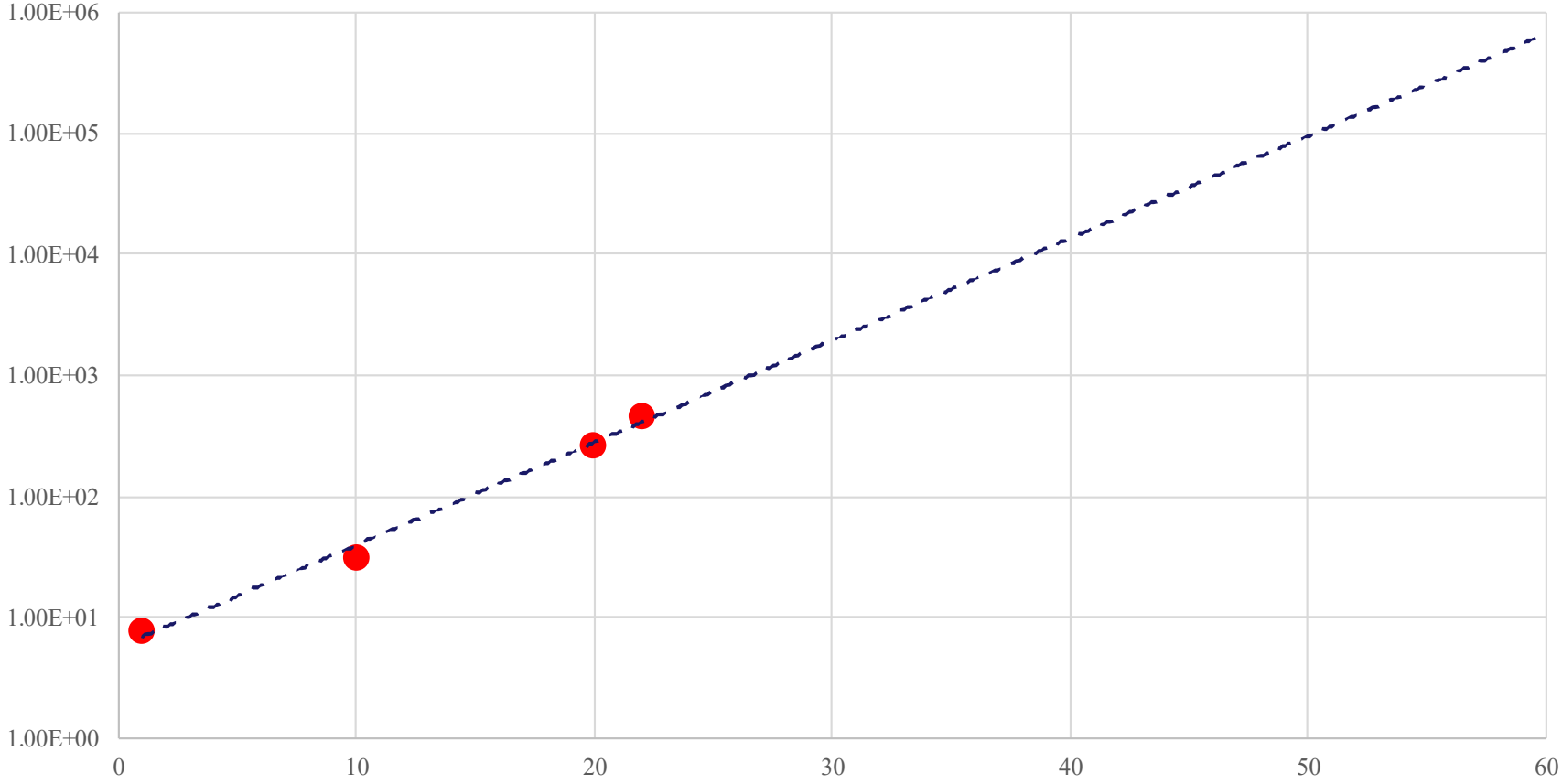
Data from https://coronavirus.1point3acres.com

Demographics



Cumulative Death in USA

Data from https://coronavirus.1point3acres.com



Days since March 1st

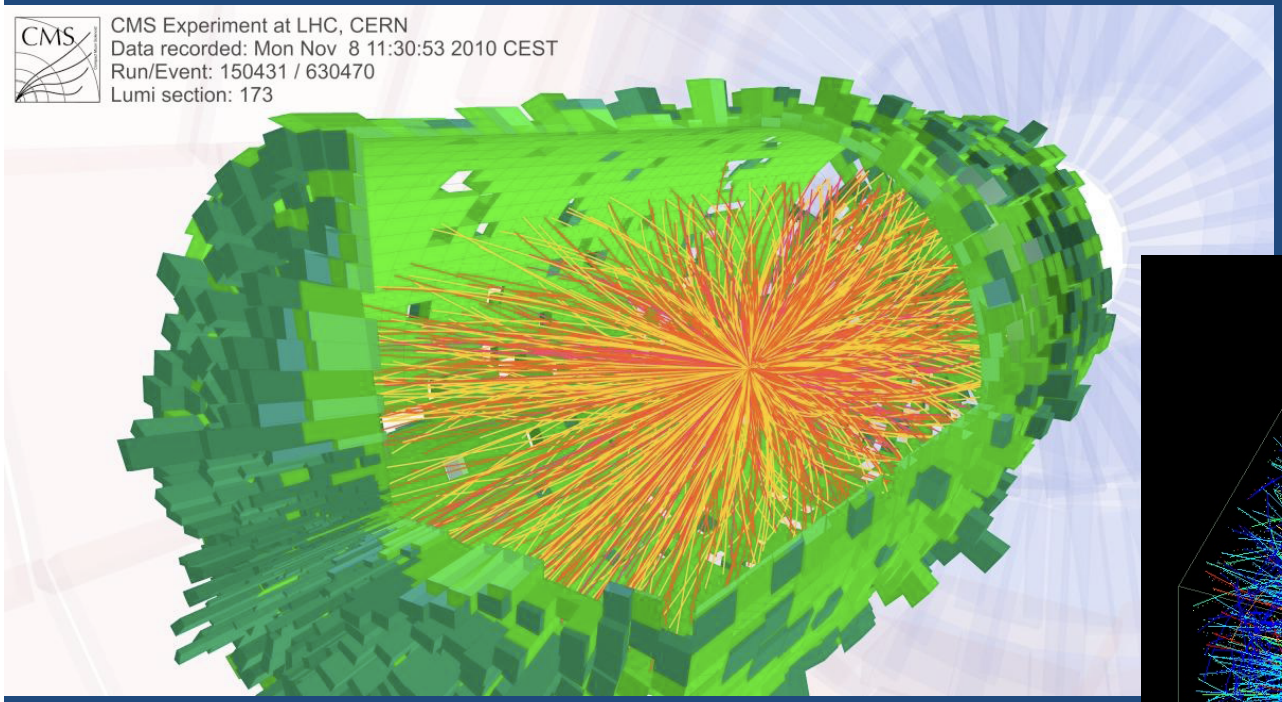
Please take social distancing and stay at home order seriously!
Wash hands with soap frequently and thoroughly at least 20 sec & take care of yourselves, your families.

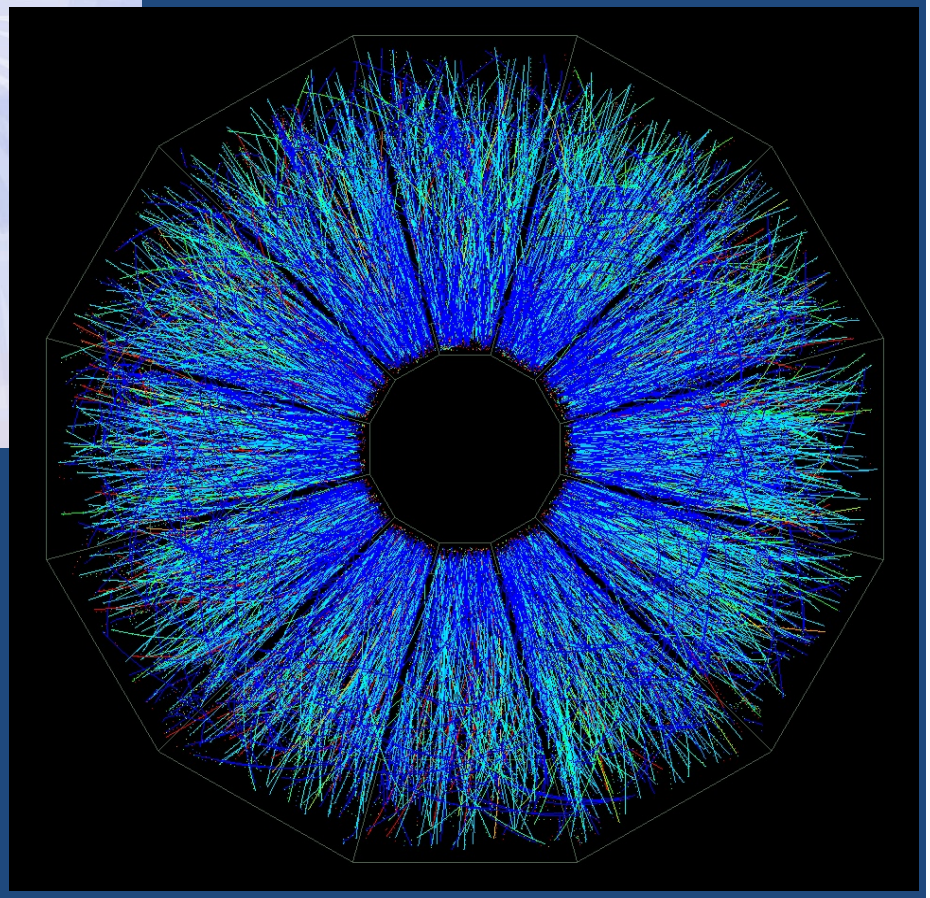
Why do we do Relativistic Heavy Ion Physics?

Goal: Create the hottest matter on earth
(Quark-Gluon Plasma)

A relativistic heavy ion collision:
Two nuclei colliding at √s ~ 1 – 10000 GeV
Thousands of new particles are produced.
The product of the collision is NOT a simple superposition of elementary nucleon-nucleon collisions.

Heavy Ion Events in Detectors:



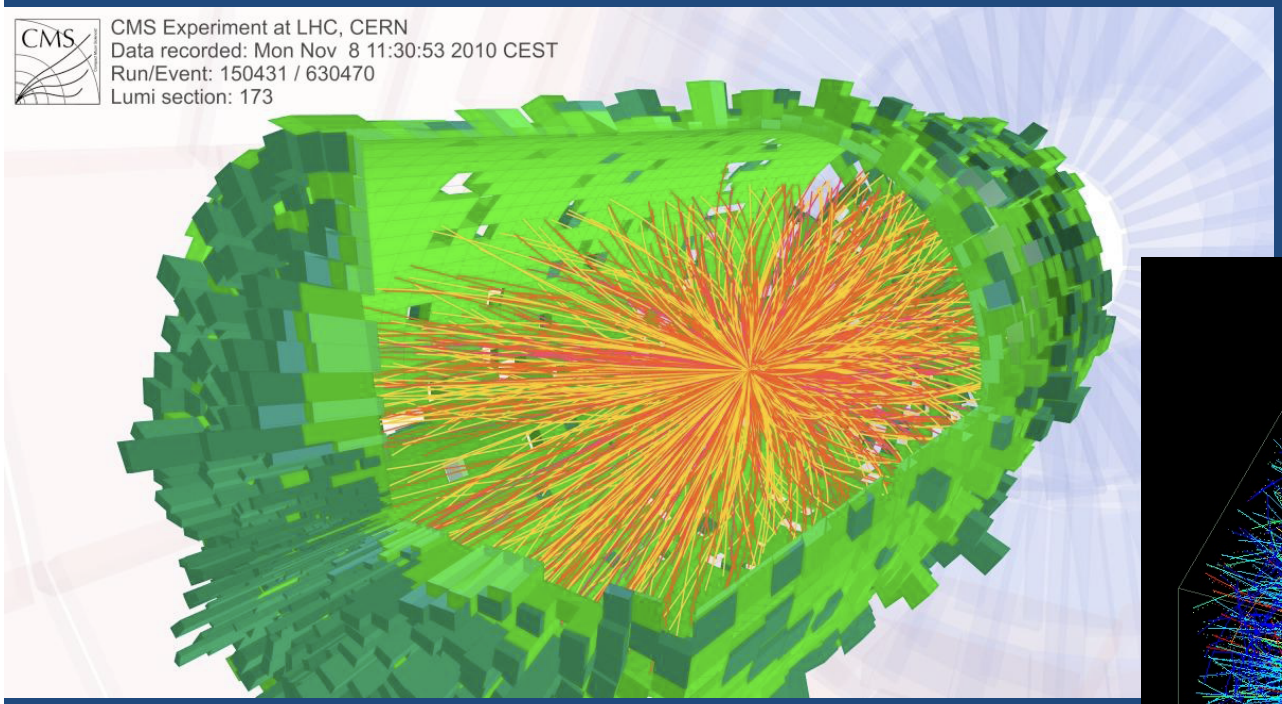


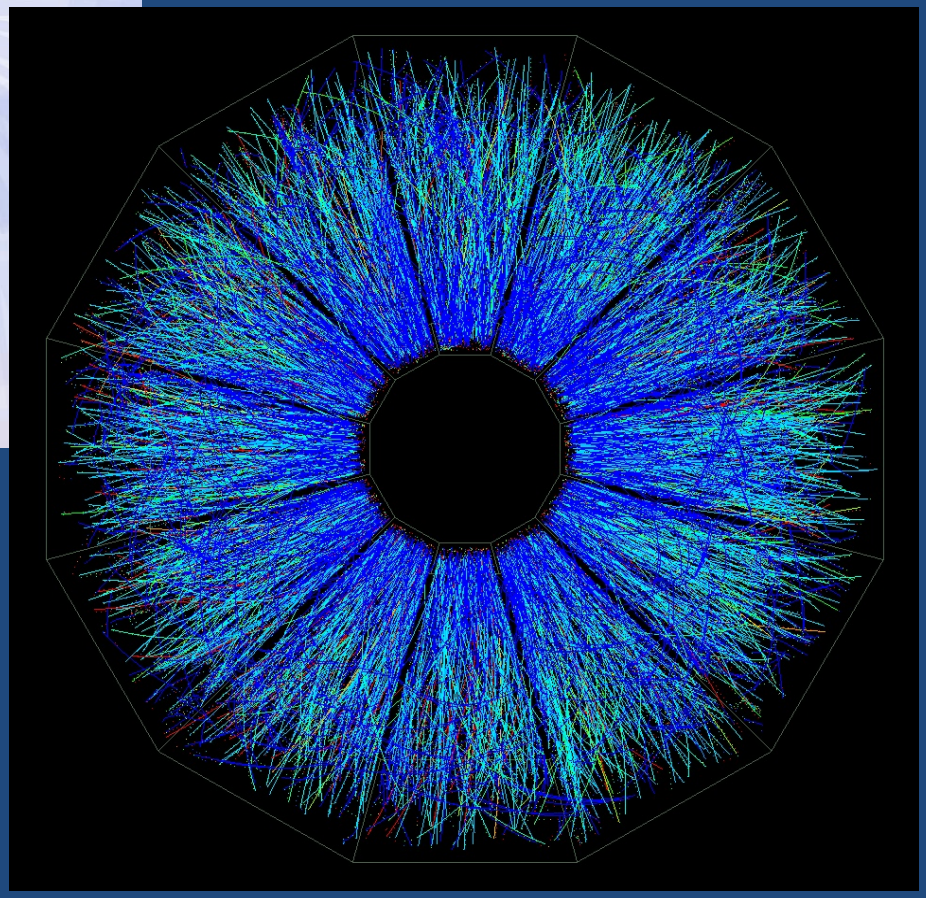
Q1: ***Why*** **measure such complexity?**

Q2: How to measure such complexity?

Q3: What did we learn so far?

Heavy Ion Events in Detectors:



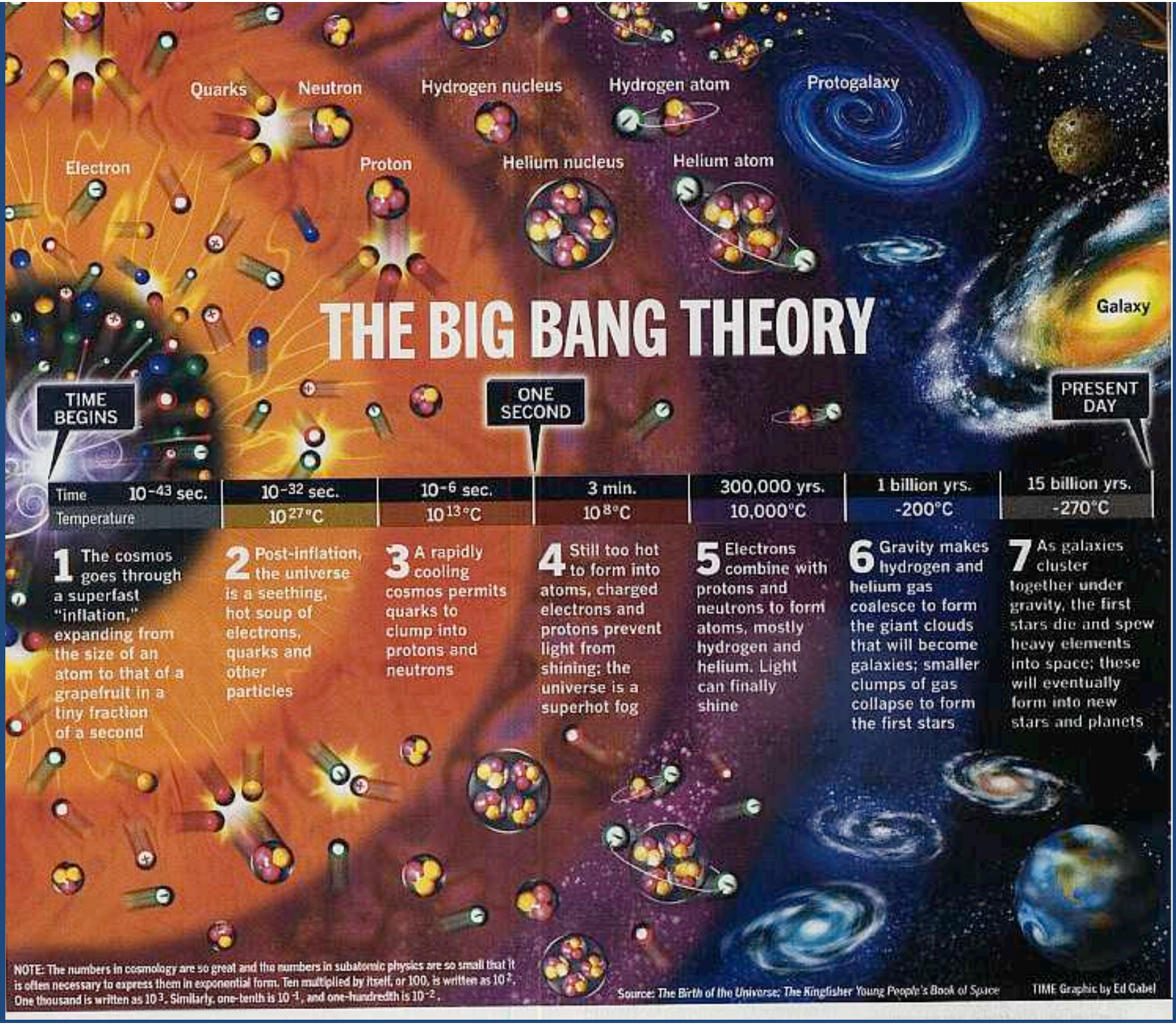


Q1: ***Why*** **measure such complexity?**

Q2: How to measure such complexity?

Q3: What did we learn so far?

- **Verify existence of QGP**
- **Study properties of QGP**
- **Use external and internal probes**
- Small viscosity perfect liquid.
- Opaque to fast partons


Quarks
Neutron
Hydrogen nucleus
Hydrogen atom
Protogalaxy
Electron
Proton
Helium nucleus
Helium atom
Galaxy
THE BIG BANG THEORY
TIME BEGINS
ONE SECOND
PRESENT DAY
Time 10⁻⁴³ sec. | 10⁻³² sec. | 10⁻⁶ sec. | 3 min. | 300,000 yrs. | 1 billion yrs. | 15 billion yrs.
Temperature 10²⁷°C | 10¹³°C | 10⁸°C | 10,000°C | -200°C | -270°C
1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second
2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles
3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons
4 Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog
5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine
6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars
7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets
NOTE: The numbers in cosmology are so great and the numbers in subatomic physics are so small that it is often necessary to express them in exponential form. Ten multiplied by itself, or 100, is written as 10², One thousand is written as 10³. Similarly, one-tenth is 10⁻¹, and one-hundredth is 10⁻².
Source: The Birth of the Universe: The Kingfisher Young People's Book of Space
TIME Graphic by Ed Gabel

Atomic nuclei and the "nuclear" force

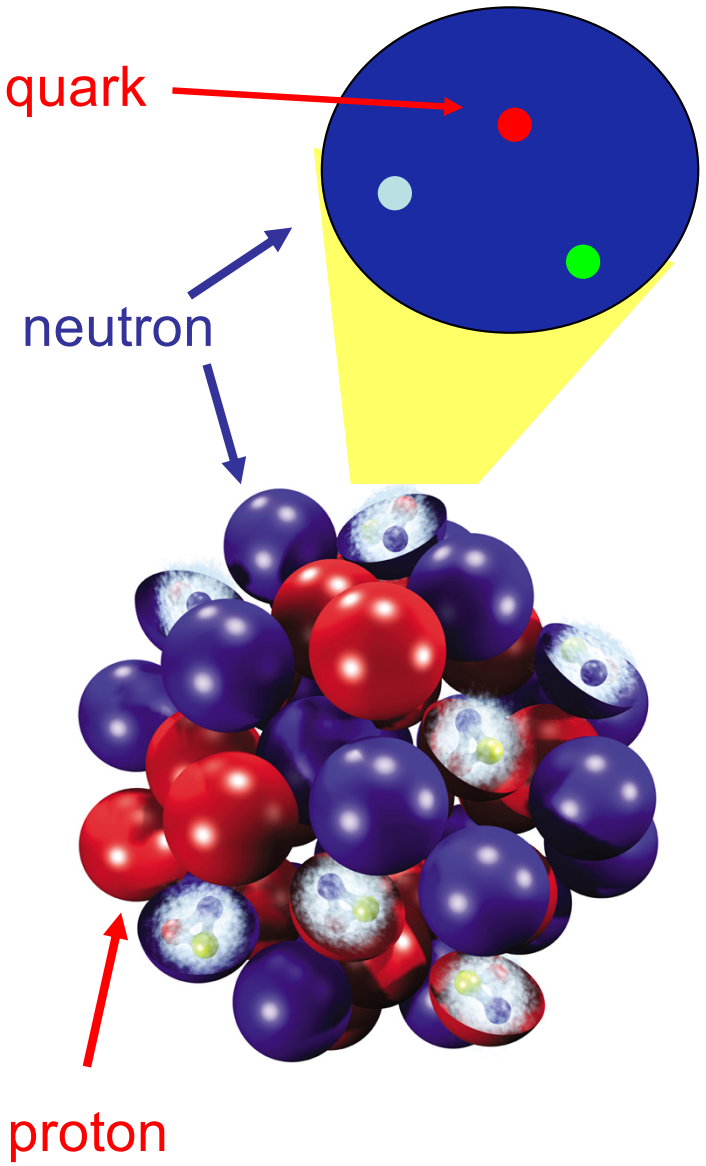
Nuclei composed of:

- protons (+ electric charge)
- neutrons (no electric charge)

Does not blow up!? → "nuclear force"

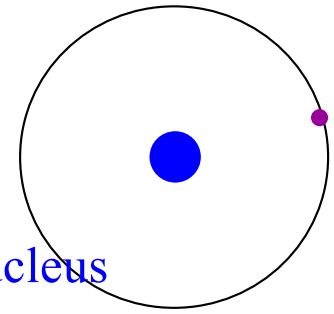
- overcomes electrical repulsion

- arises from fundamental strong force (#3)
  - acts on color charge of **quarks**



How to measure such a complexity?
An analogy… and a difference!

to study structure of an atom…



neutral atom

…separate constituents

Imagine our understanding of atoms or QED if we could not isolate charged objects!!

How to measure such a complexity?
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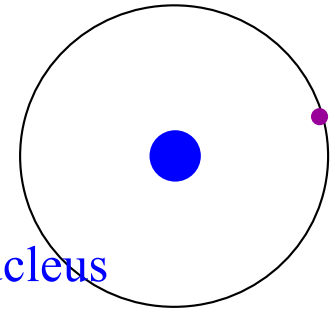
to study structure of an atom…

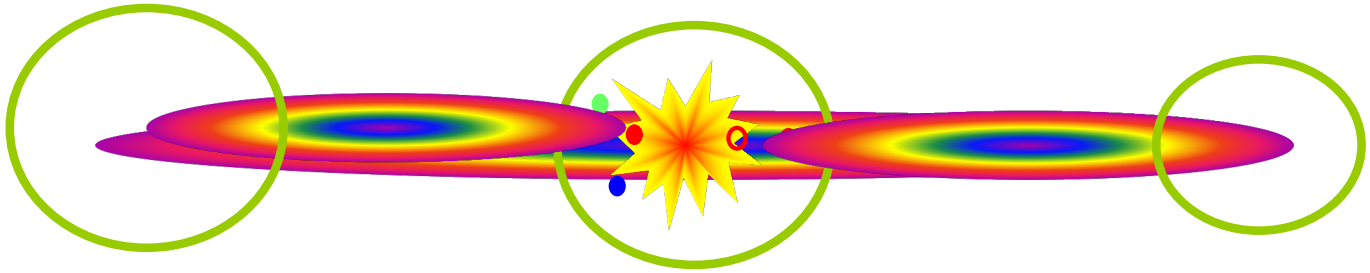


…separate constituents

Imagine our understanding of atoms or QED if we could not isolate charged objects!!

Confinement: fundamental & crucial (but *not* understood!) feature of strong force
- colored objects (quarks) have ∞ energy in normal vacuum

- **$E=mc^2$!**



"white" proton (confined quarks)

"white" proton

"white" π^0 (confined quarks)

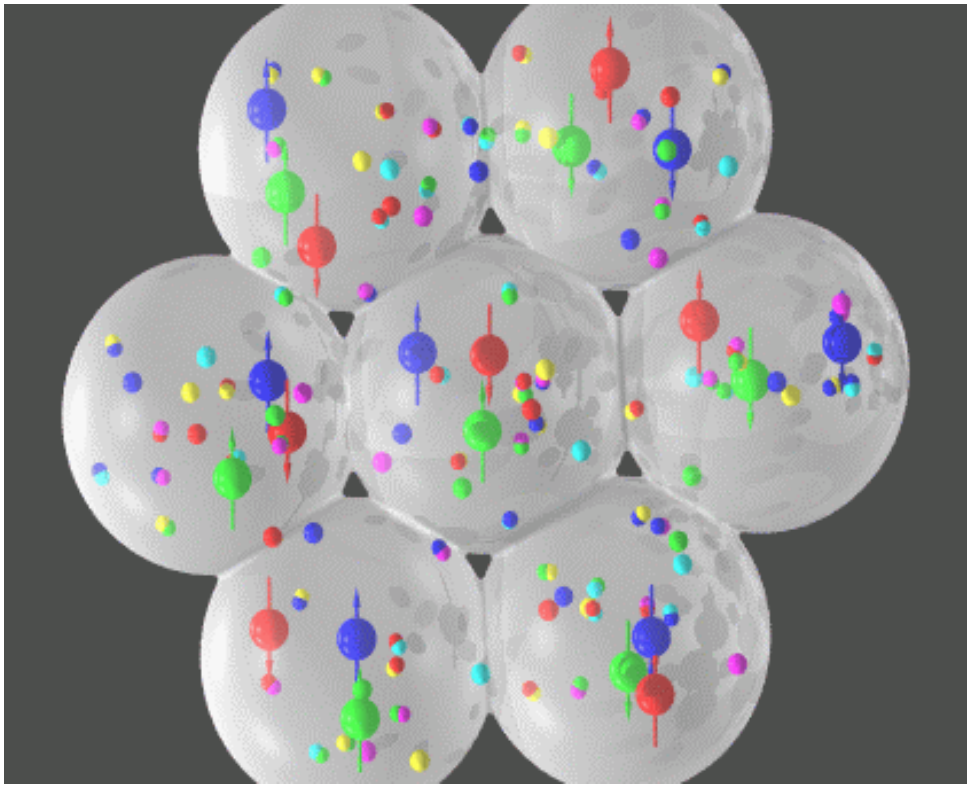
Increase the temperature and pressure.

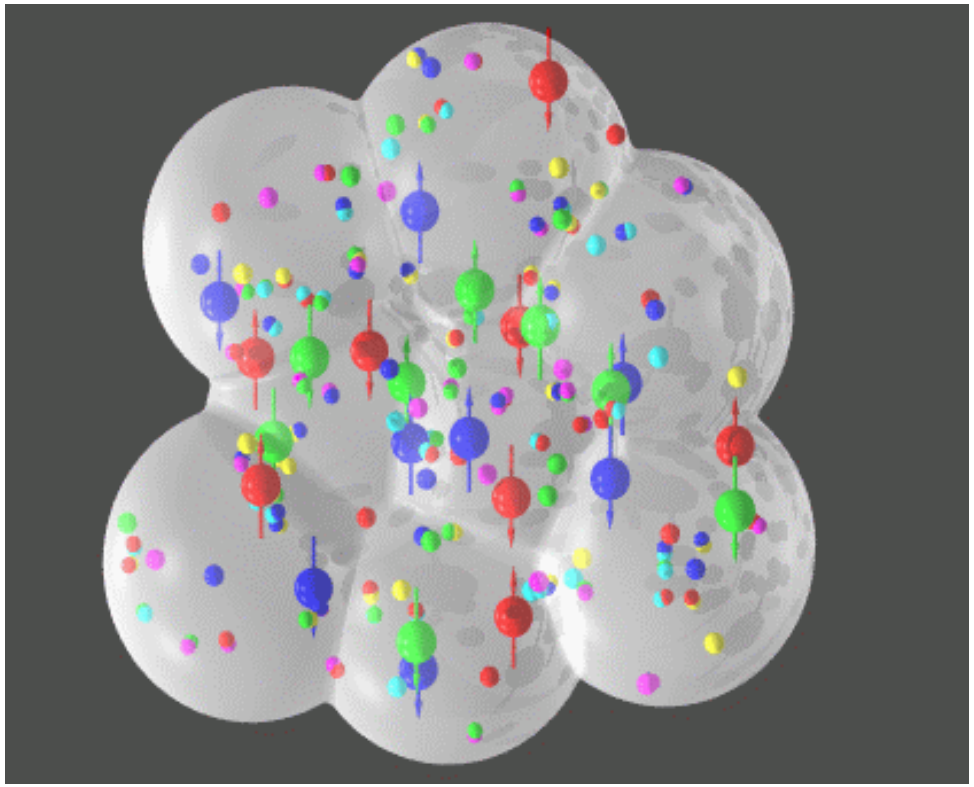
Crush matter into a soup of its constituents.

Hadronic matter

Quark gluon plasma

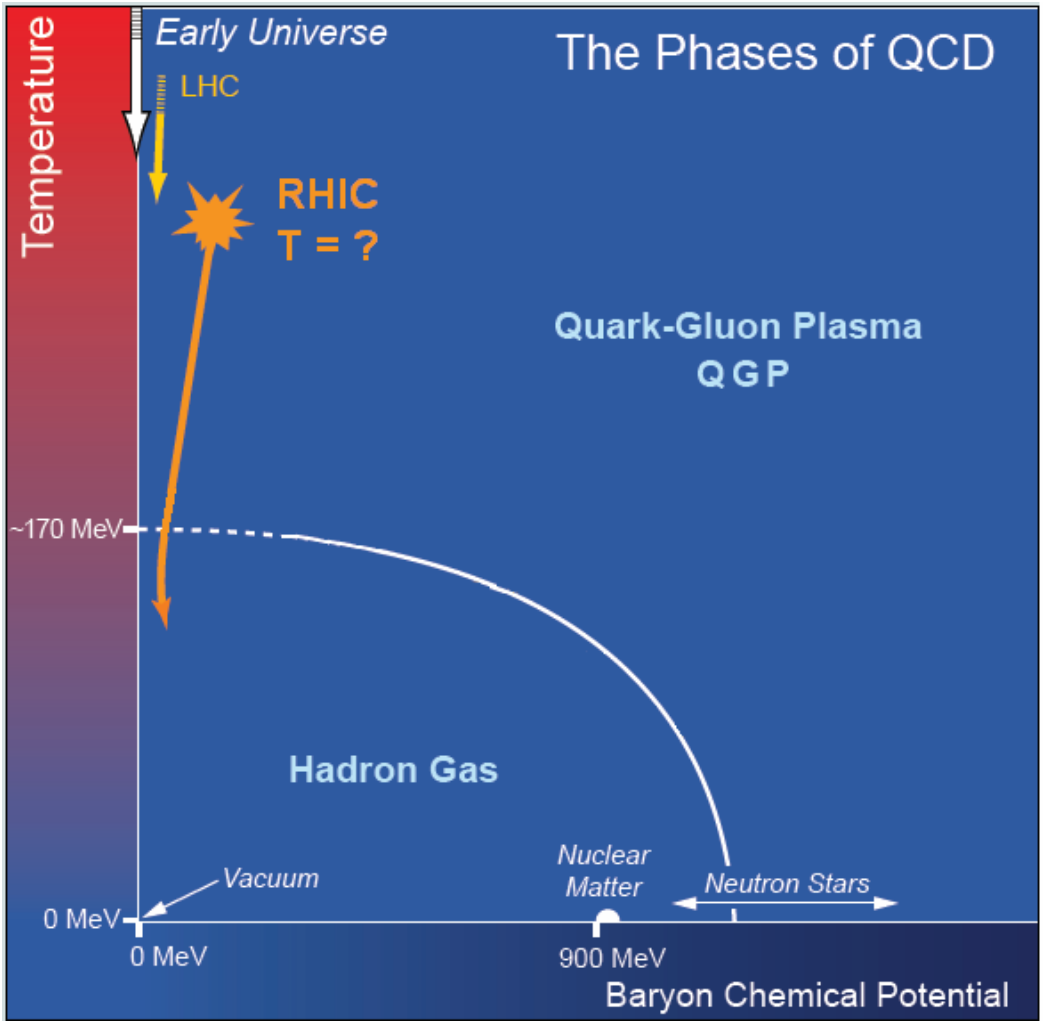
A very hot soup at ~10^{12}K





Sevil Salur

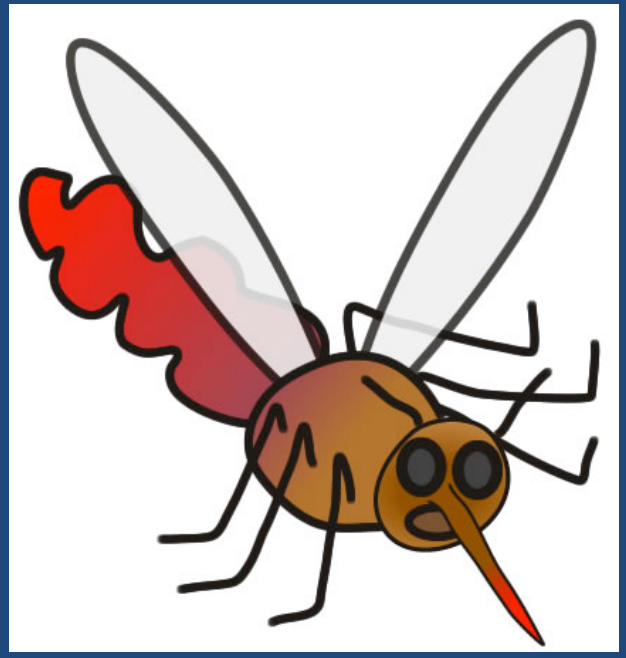
The Landscape of QCD



Heavy Ion Collisions at RHIC and LHC create conditions sufficient to “melt” matter into a quark gluon plasma

Heavy ion collisions → **HOT** matter

- Room Temperature: 300 K = 0.025 eV
- Fire: 1000-2000 K: ~0.12 eV
- Sun :
  - Surface: 5000 K: ~0.4 eV
  - Corona: 5 x 10^6 K ~ 400 eV
  - Core: 15 x 10^6 K ~ 1 keV
- Heavy ion collision :
  - T_c ~ 2 x 10^{12} K ~170 MeV
    - Temperature of deconfinement



1 TeV: A trillion electronvolts ~ the kinetic energy of a flying mosquito.

1 Electron Volt (eV) = 1.6 x 10^{-19} Joules

How can we study the thermodynamics of the STRONG force?

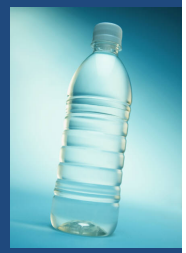
Imagine…

You know that ice exists…

Imagine…

You know that ice exists…

Your theory friends with huge computers tell you that there is something called water…



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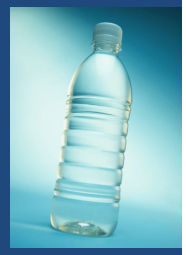

You don’t have a way to heat ice…

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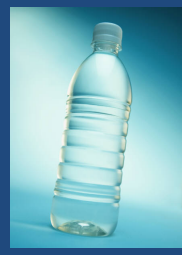
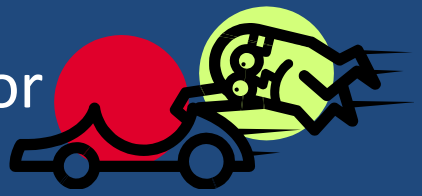


You don’t have a way to heat ice…

So you put millions of ice cubes in an ice- accelerator



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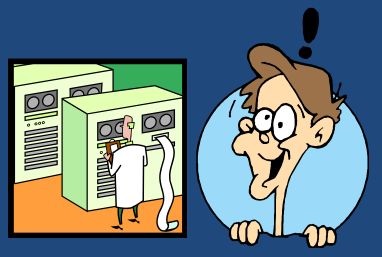

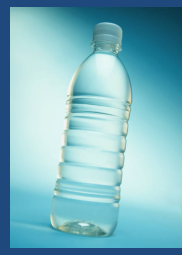

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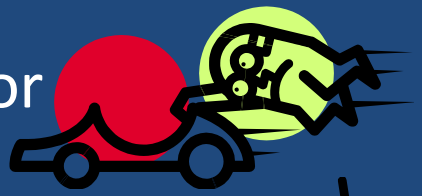

Send them at 99.995% of the speed of light to collide
Generating thousands of ice-cube+ice-cube collisions per second…

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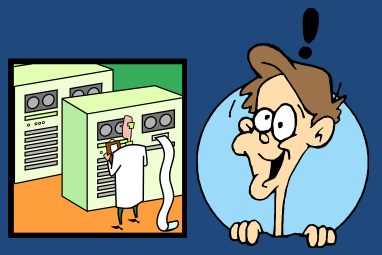

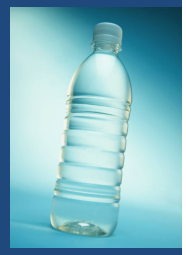

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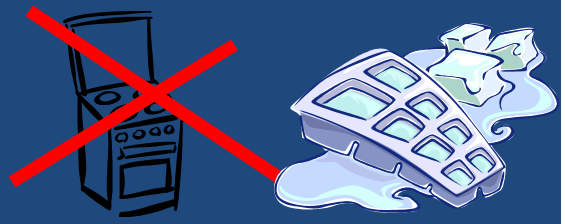

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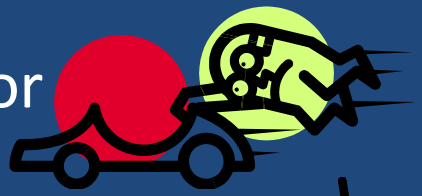


Send them at 99.995% of the speed of light to collide
Generating thousands of ice-cube+ice-cube collisions per second…

And you watch it all from the vicinity of Mars!

Sevil Salur

Producing “Bulk” nuclear Matter in the laboratory.

We must create/compress/heat a **bulk** (geometrically large) system

Freeze/melt a single H_20 molecule?

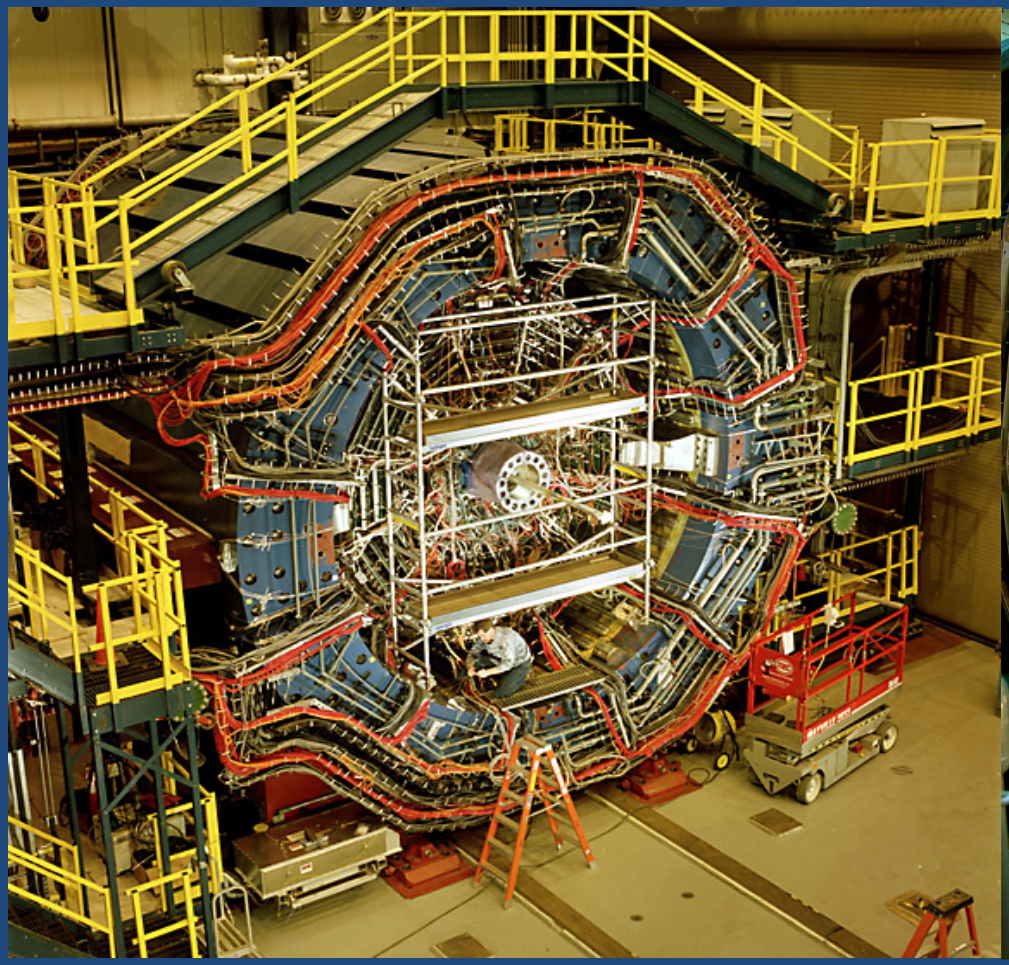
Fundamental distinction from particle physics

Only achievable through collisions of the heaviest nuclei (Au, Pb) at the highest available energy– Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC)


PHOBOS
PHENIX
BRAHMS
STAR

- **RHIC = Relativistic Heavy Ion Collider**
  - 3.83 km circumference
  - Two independent rings
    - 120 bunches/ring
  - Capable of colliding ~any nuclear species on ~any other species
  - Energy:
    - Up to 500 GeV for p+p
    - Up to 200 GeV for Au+Au (per N-N collision)
  - Luminosity
    - Au+Au: 2×10^{26} cm^{-2} s^{-1}
    - p+p : 2×10^{32} cm^{-2} s^{-1} (*polarized*)

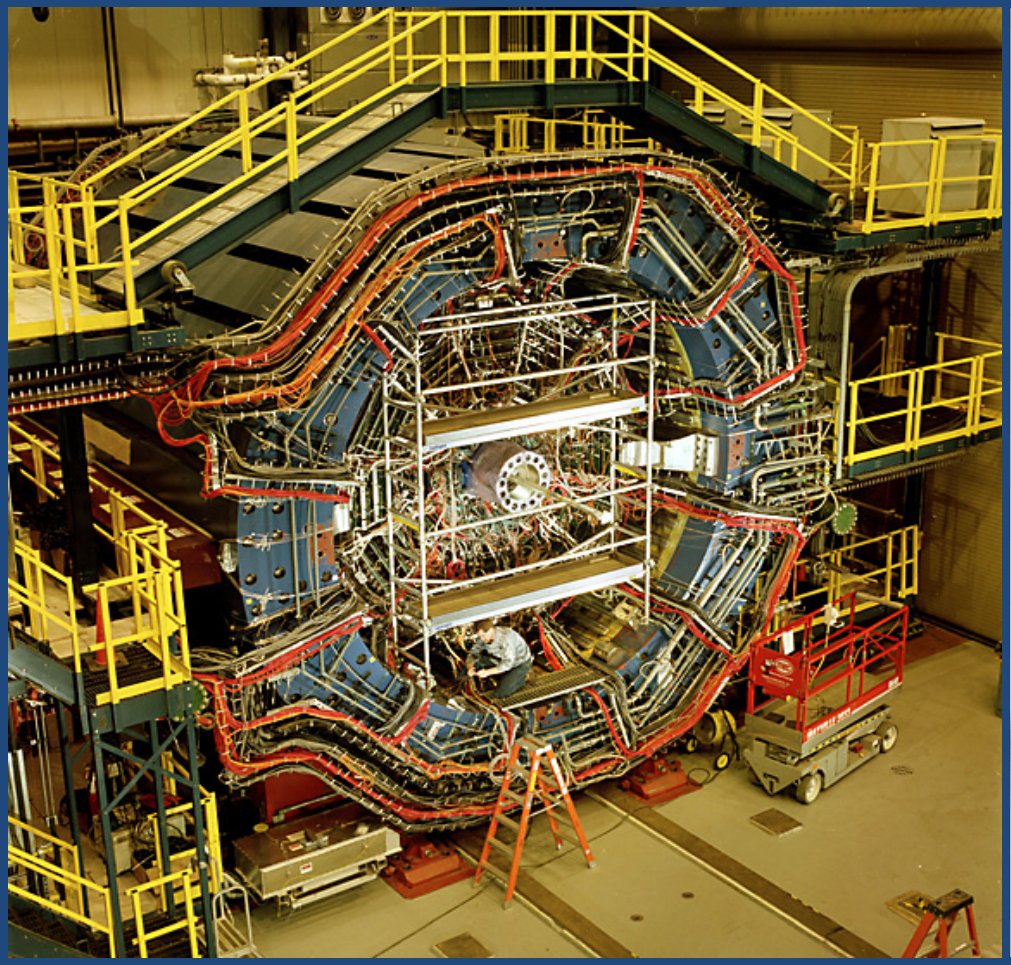
RHIC Experiments

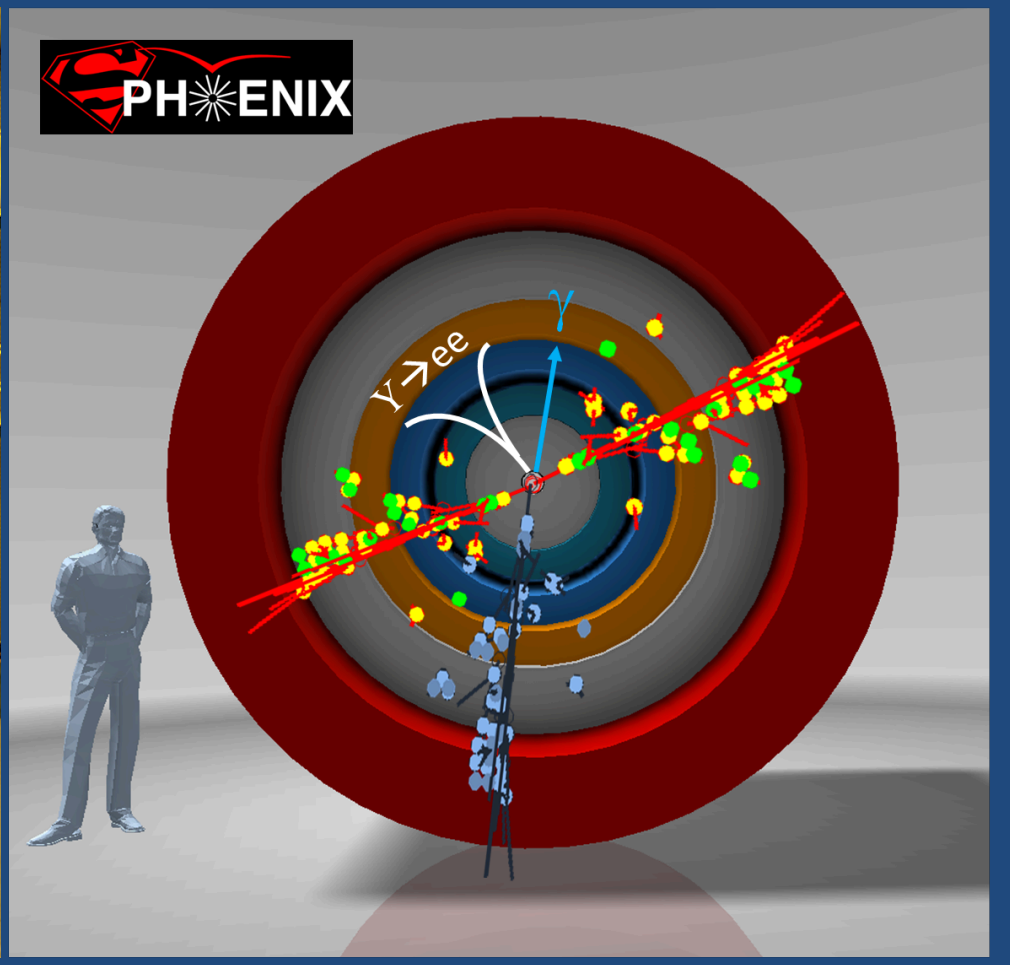


STAR ~550 Collaborators
specialty: large acceptance
Hadronic Observables
Jets & Di-Hadron Physics
High-pT Quarkonia

PHENIX ~550 Collaborators
specialty: rare probes, leptons, and photons

RHIC Experiments





STAR ~550 Collaborators
specialty: large acceptance
Hadronic Observables
Jets & Di-Hadron Physics
High-pT Quarkonia

S-PHENIX ~ Jet Physics at RHIC!

LHC:The Next Frontier….

LHC = Large Hadron Collider

LHC is not only a p+p machine!

At least 4 weeks in a year is devoted for heavy ions…

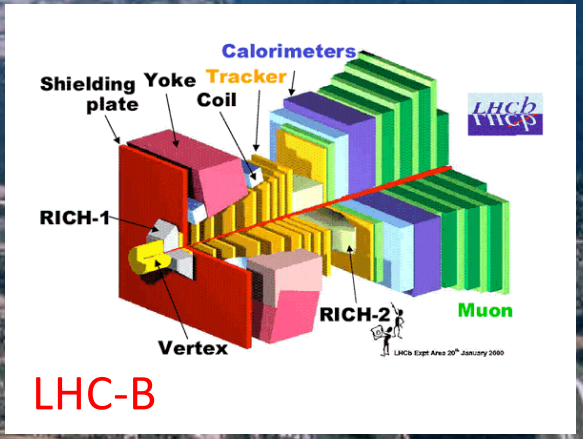
- **27 km circumference**
- **100 m underground**
- **Two independent rings**
- **Capable of colliding**
  ~any nuclear species
  on
  ~any other species
- **Energy:**
  - **Up to 14000 GeV for p+p**
  - **Up to 5500 GeV for Pb+Pb (per N-N collision)**

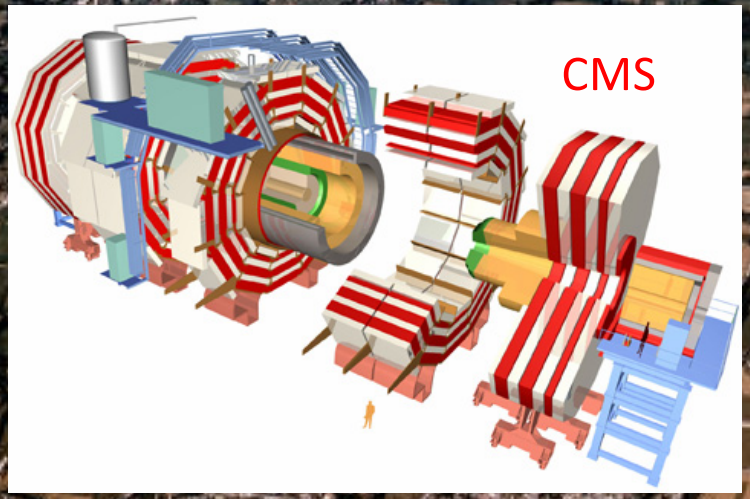
LHC Heavy Ion program started in late 2010!

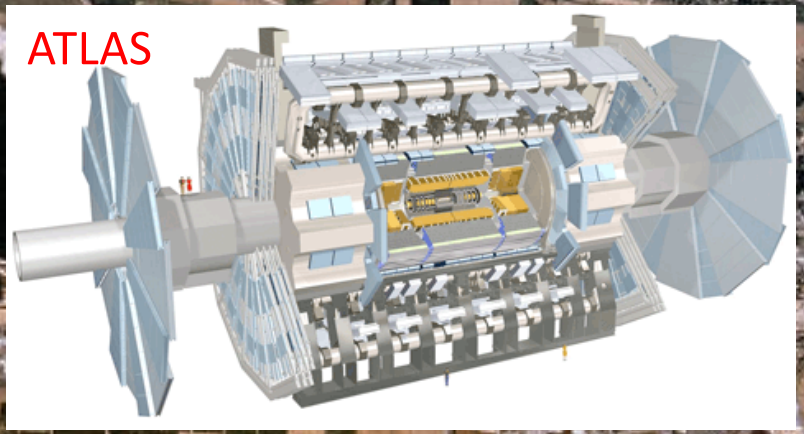
Run 1 (2010-2014)

Run 2 (2015-2018)

Run 3 And Beyond…







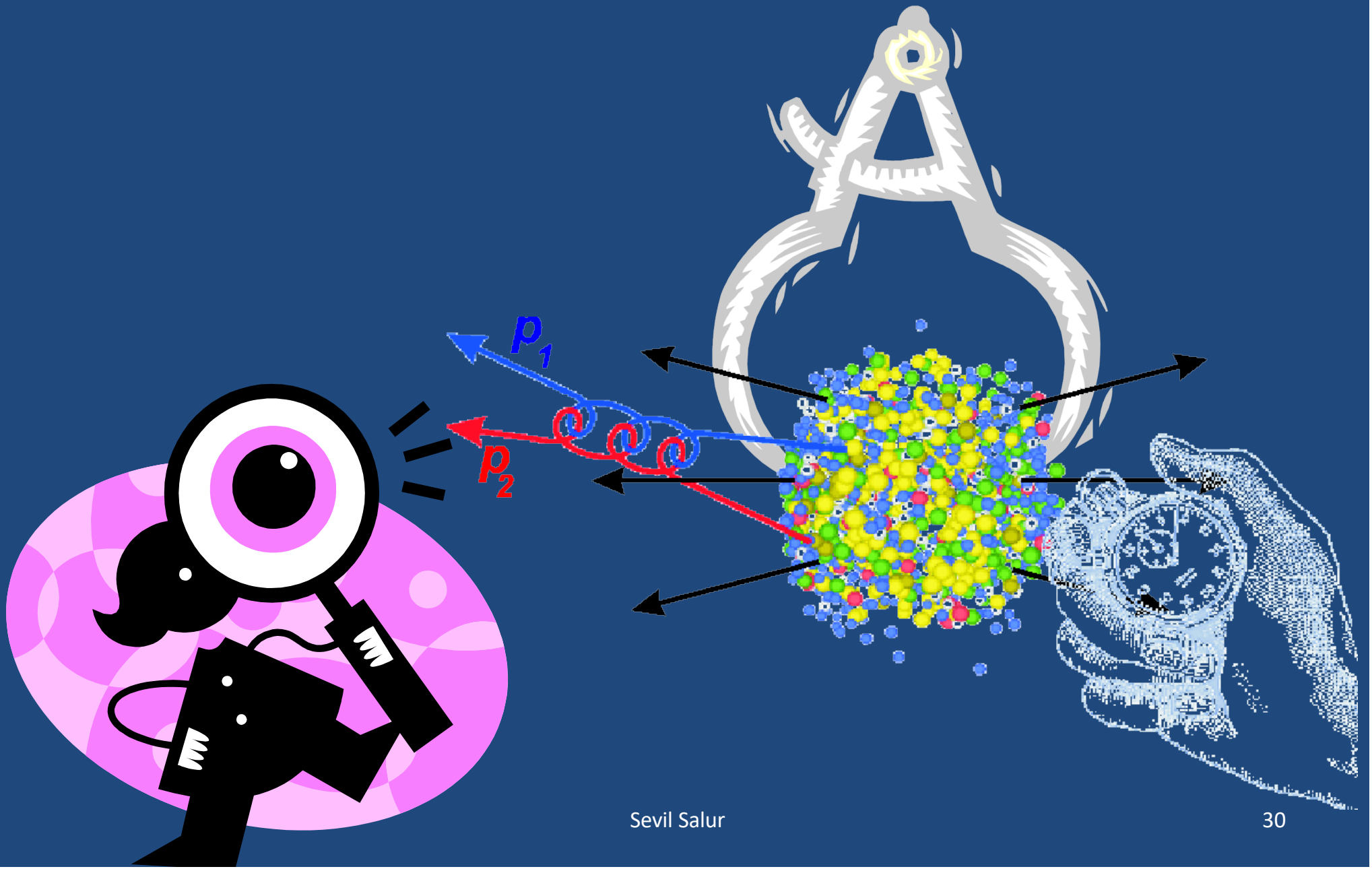
Why Study Heavy Ion Collisions at LHC ?

Central collisions	SPS	RHIC	LHC
$s^{1/2}$(GeV)	17	200	5500
dN_{ch}/dy	500	700-1500	3-10 $x10^3$
ε (GeV/fm^3)	2.5	3.5-7.5	15-40
τ_{QGP} (fm/c)	<1	1.5-4.0	4-10

J. Schukraft QM2001

LHC provides a **critical** lever arm in energy.

So, what have we seen?



Experimental search for “interesting” phenomena

- Look at elementary p+p collisions
  - Measure an observable (e.g. Jet production)
- Look at Heavy Ion collisions
  - Measure the same observable as we do in p+p
- Compare them, is there something new?

Jets: What is that?

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Jets breaking the sound barrier.
The white halo → condensed water droplets (drop in air pressure around the aircraft.)

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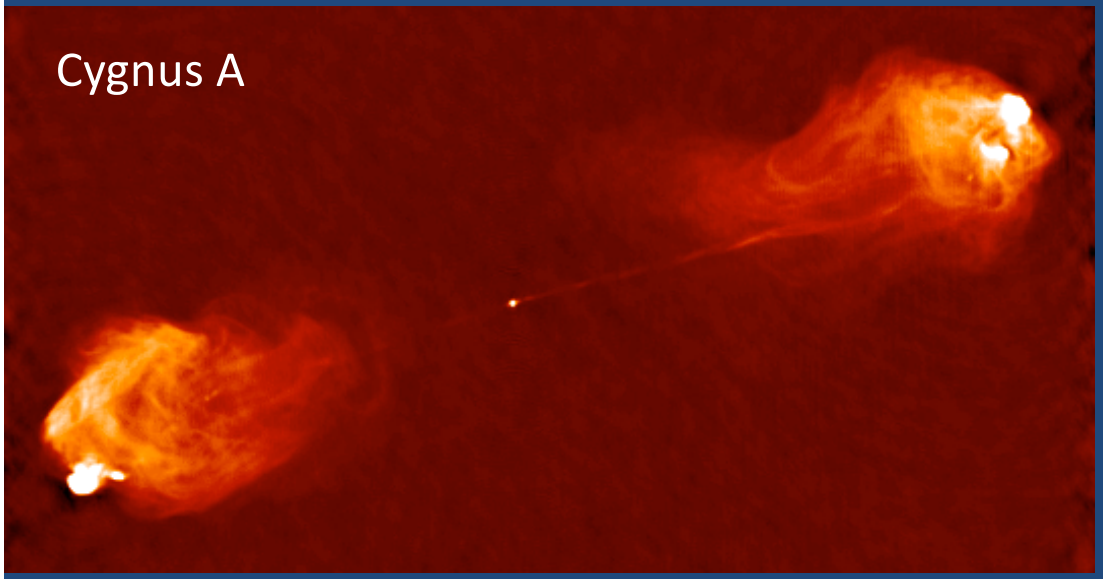

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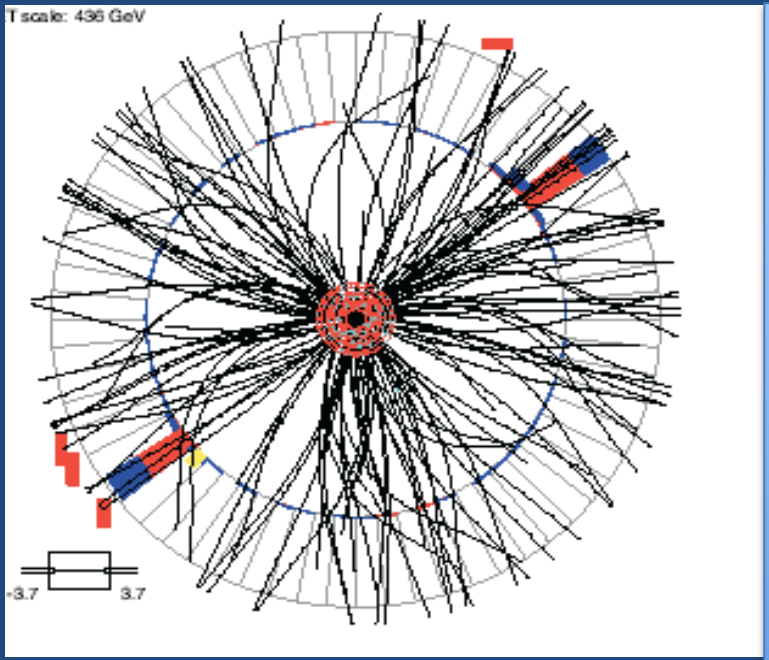
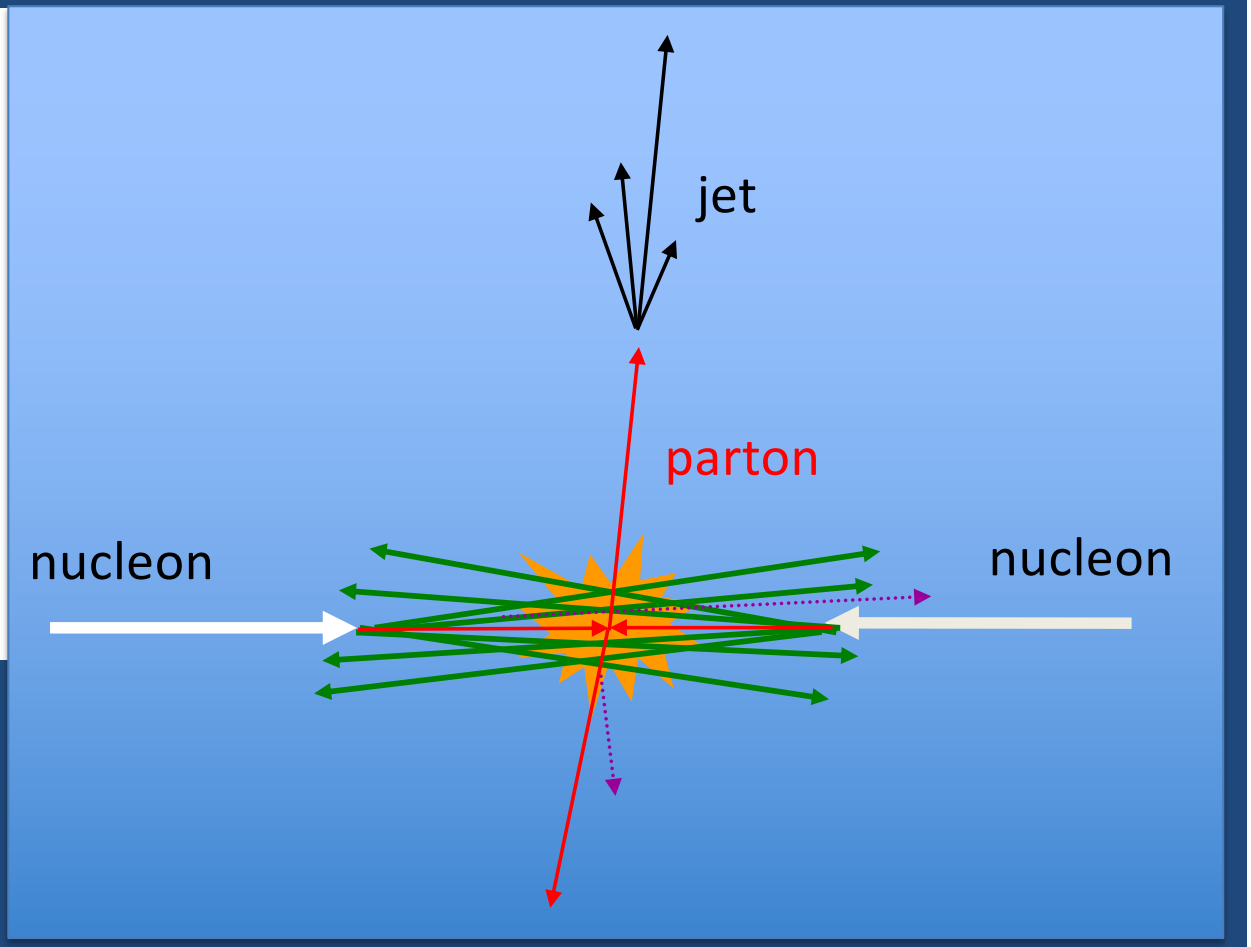
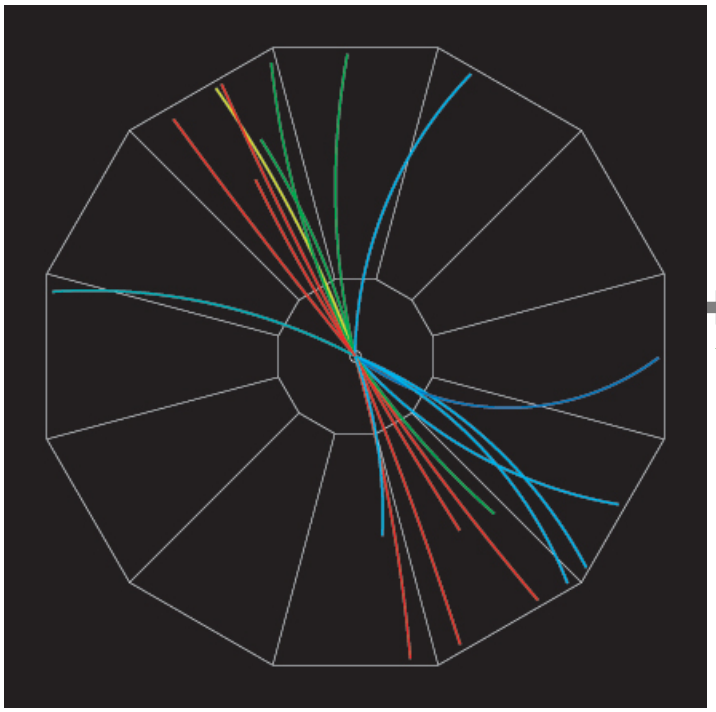


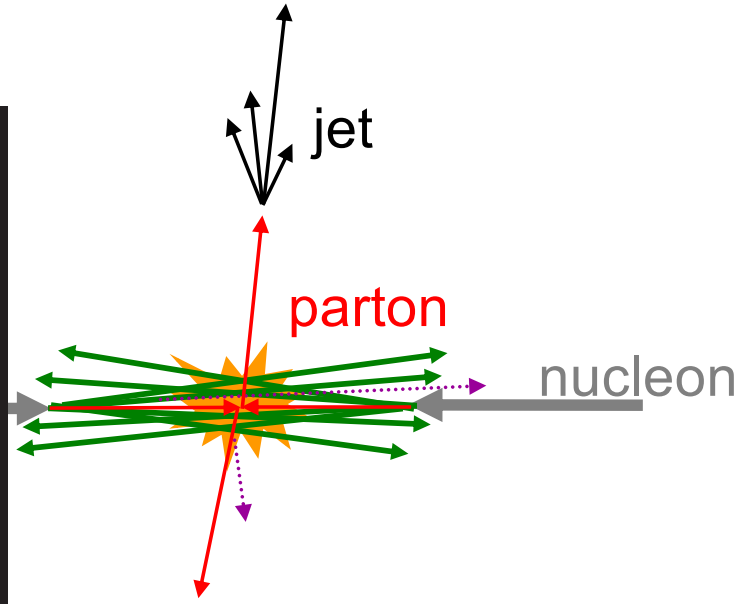


- “Jets” are generated by a collision between fast quarks and gluons (partons).
- The outgoing quark or gluon can’t exist in the vacuum (confinement!) and “fragments” into a spray of particles.
- The particles can be seen in the detector, they are very close in angle, like a “jet” of water drops coming out of a hose.

Jets in Heavy Ion Collisions

Find this …



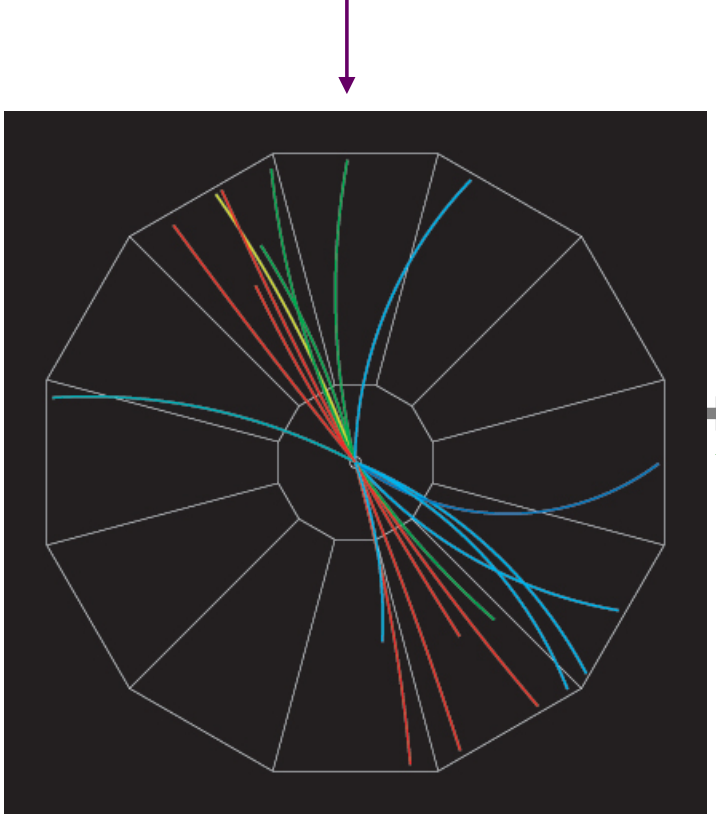


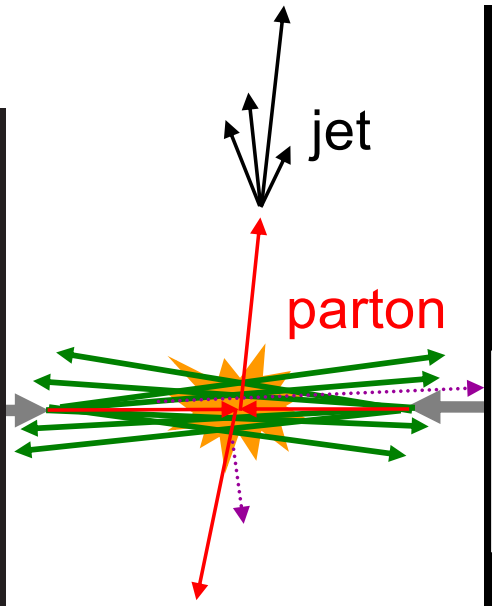
p+p →jet+jet
(STAR@RHIC)

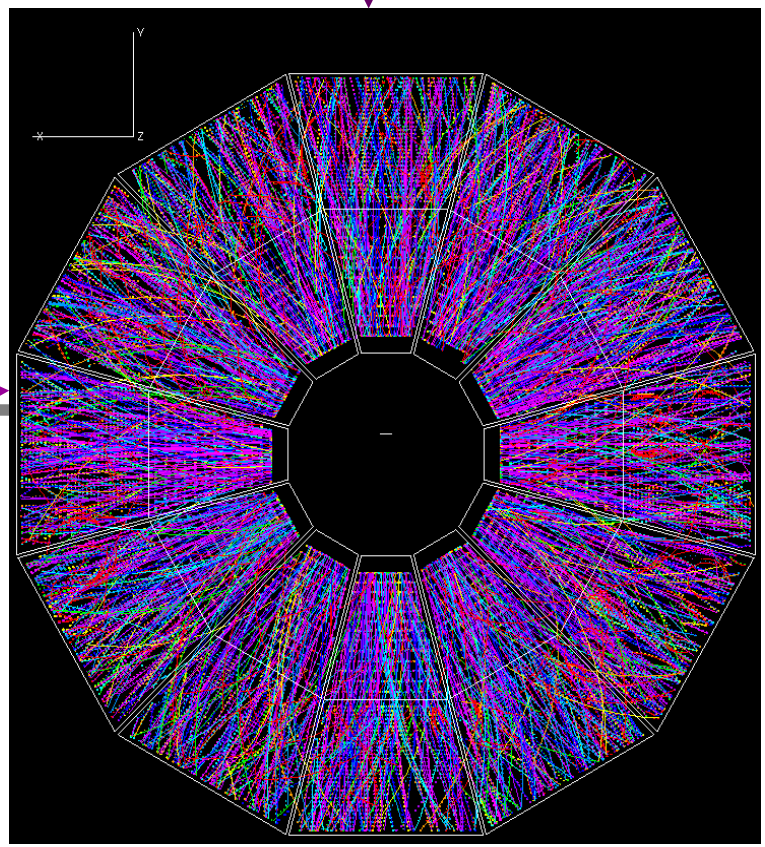
Jets in Heavy Ion Collisions

Find this …

in this !!!







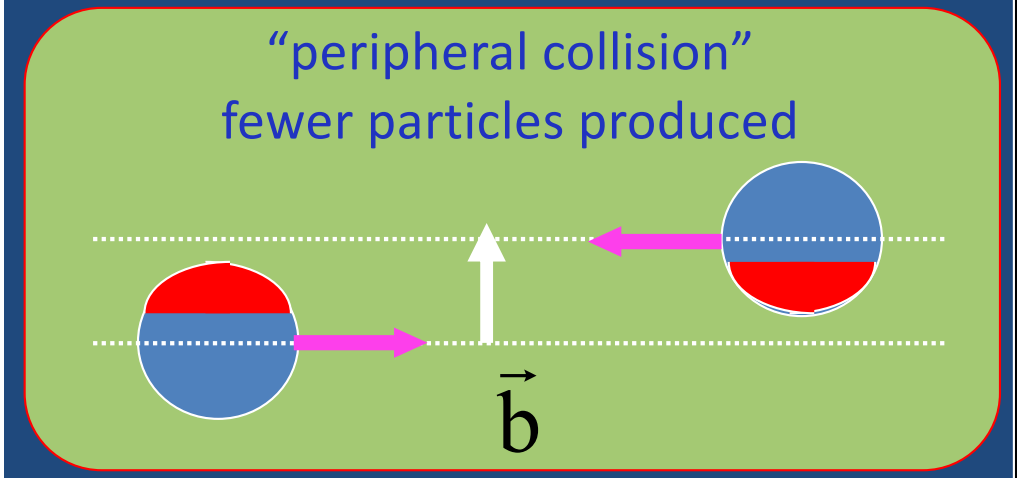
p+p →jet+jet
(STAR@RHIC)

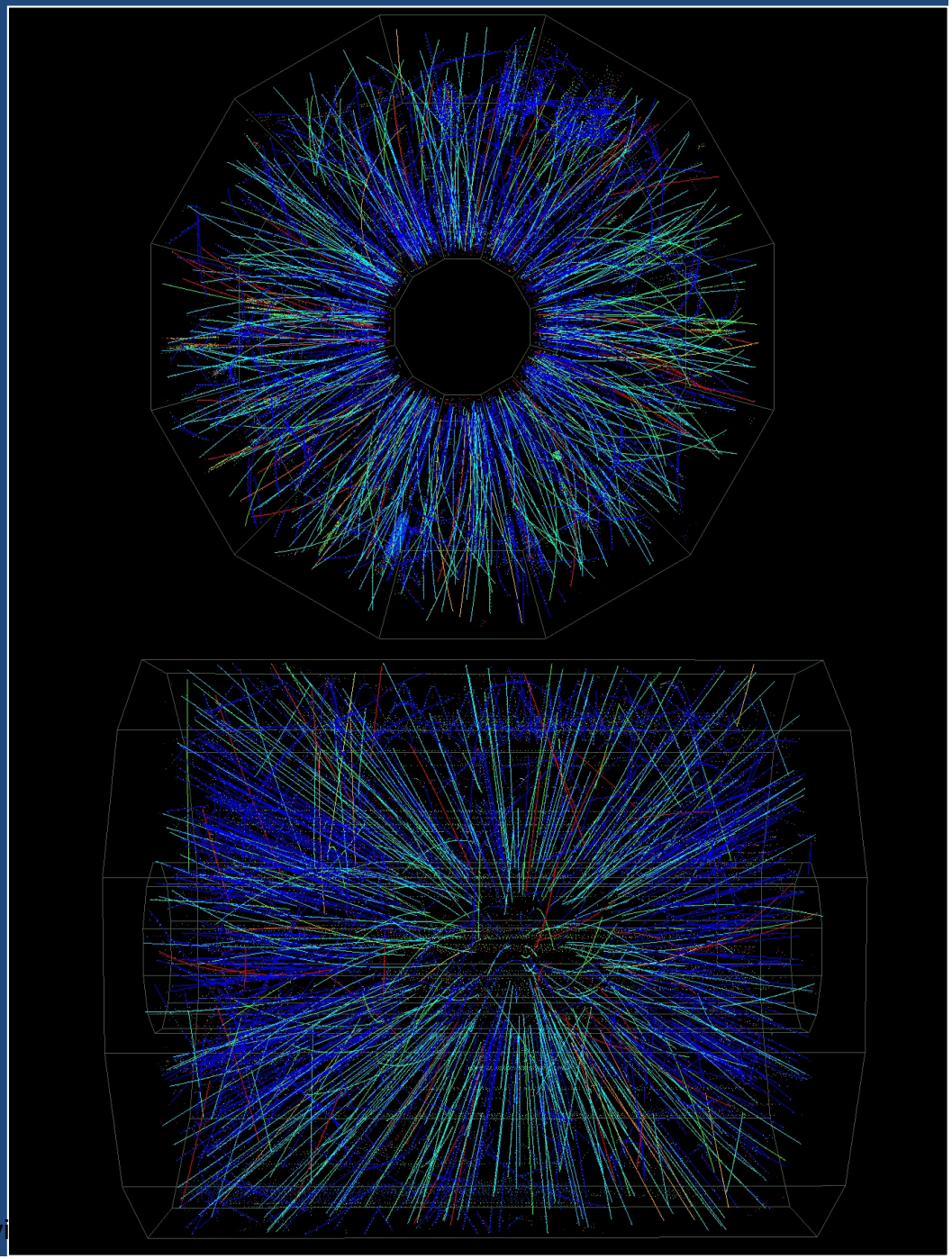
Au+Au →???
(STAR@RHIC)

Geometry Matters!

Impact parameter vector $\vec{b}$:

- $\perp$ beam direction
- connects centers of colliding nuclei



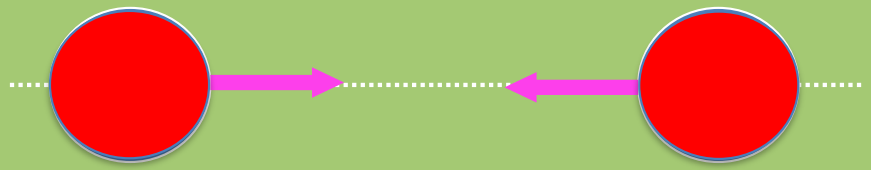


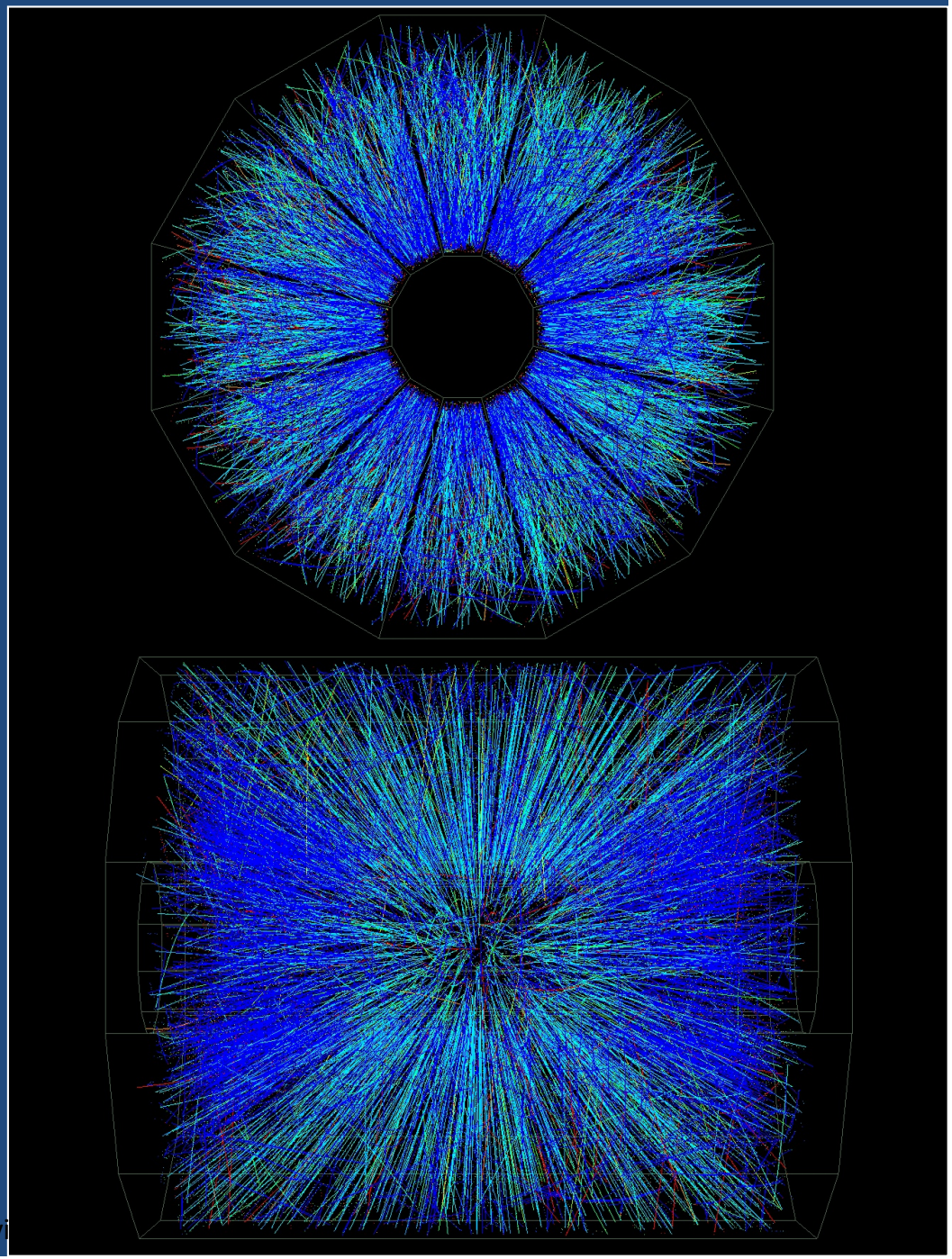
Geometry Matters!

Impact parameter vector $\vec{b}$:

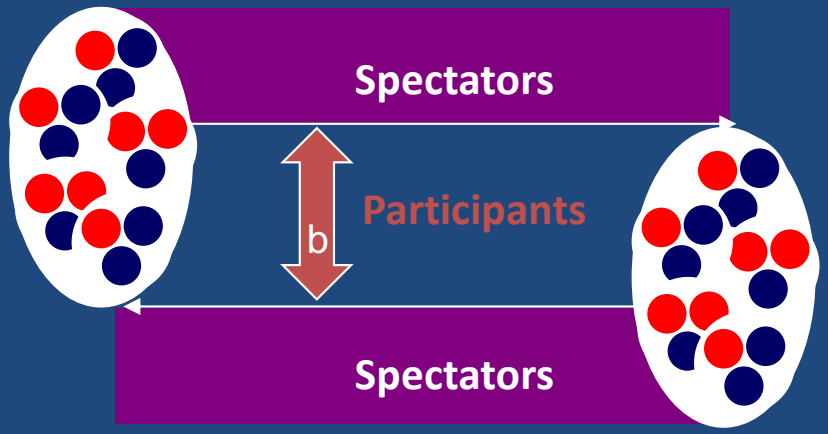
- $\perp$ beam direction
- connects centers of colliding nuclei

b = 0 $\leftrightarrow$ "central collision"
many particles produced



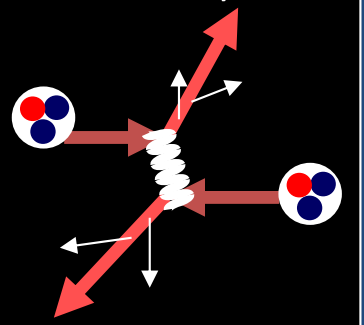


Terminology: Centrality of A+A Collisions



Number of Binary Collisions:
(# of inelastic nucleon+nucleon collisions)

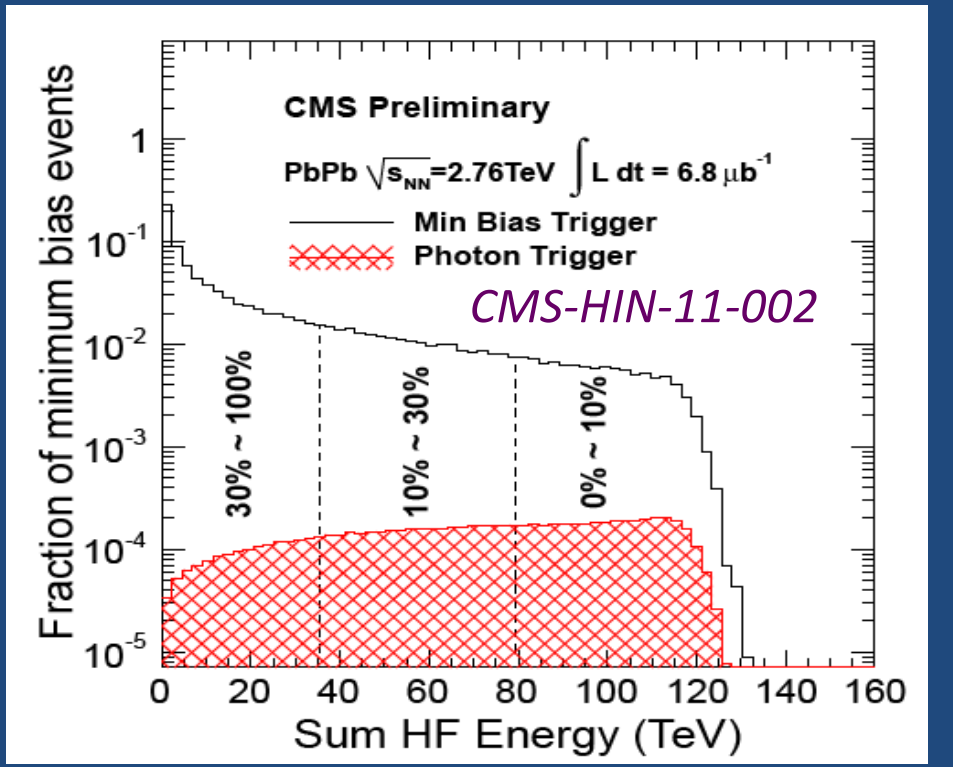
1. Jet Production
2. Heavy Flavor (s,c,b)



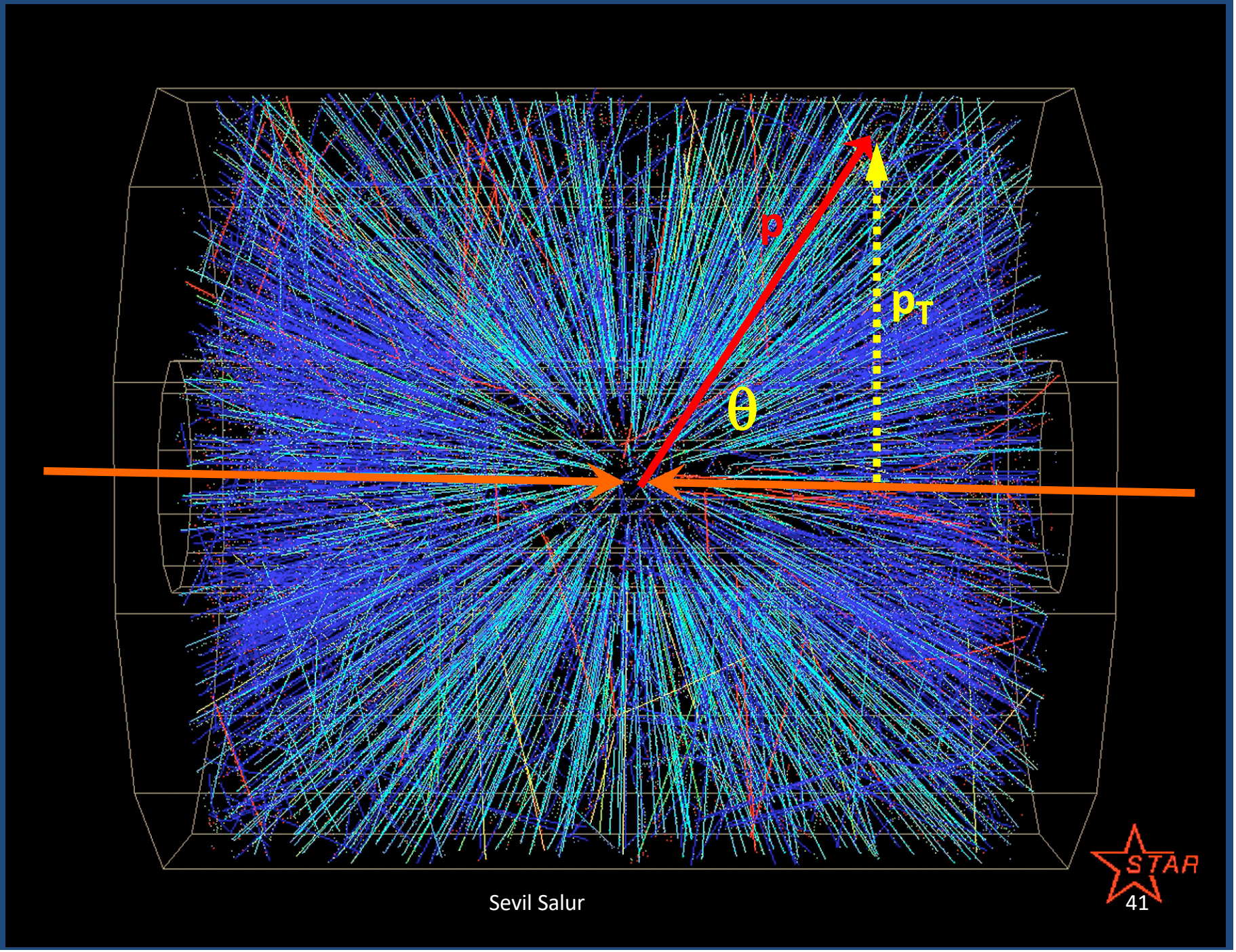
Fraction of cross section "centrality"

Number of Participant:
(# of incoming nucleons in the overlap area)

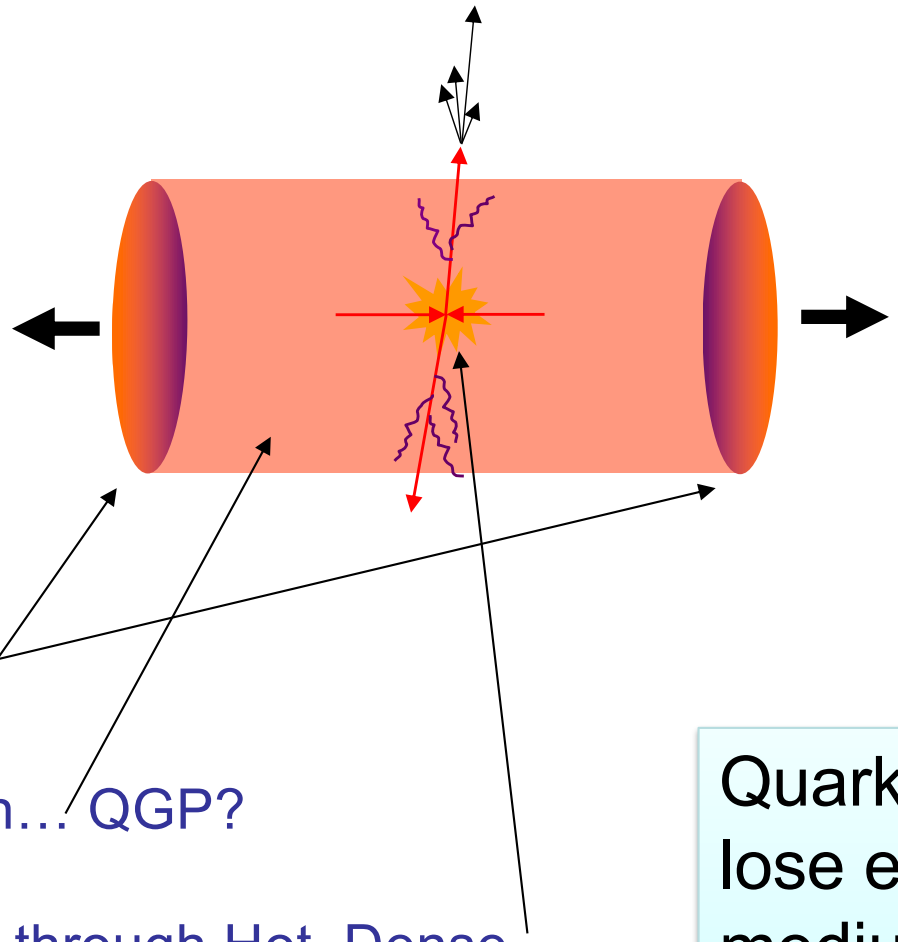
1. Soft Hadron Production
2. Transverse Energy



Transverse Dynamics



What happens to jets in a head-on Nuclear collision?



Speeding Nuclei

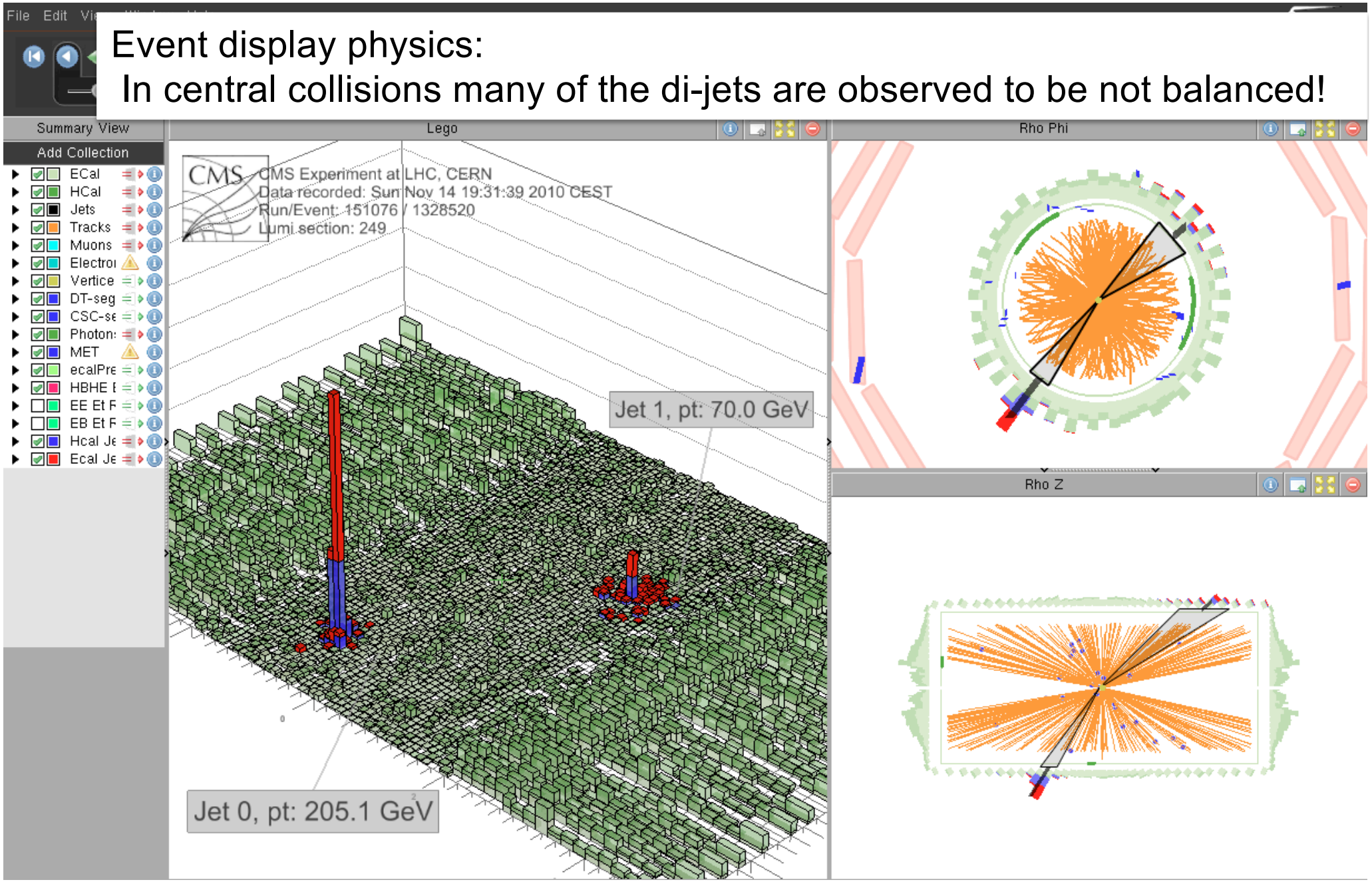
Hot, Dense region… QGP?

Jets have to pass through Hot, Dense Zone!

Quarks and gluons lose energy in dense medium generated in collision

Jets: Lessons learned:

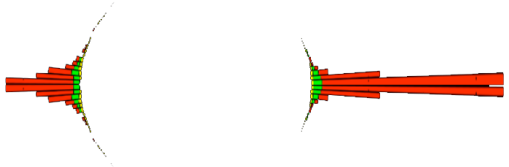
Event display physics:
In central collisions many of the di-jets are observed to be not balanced!



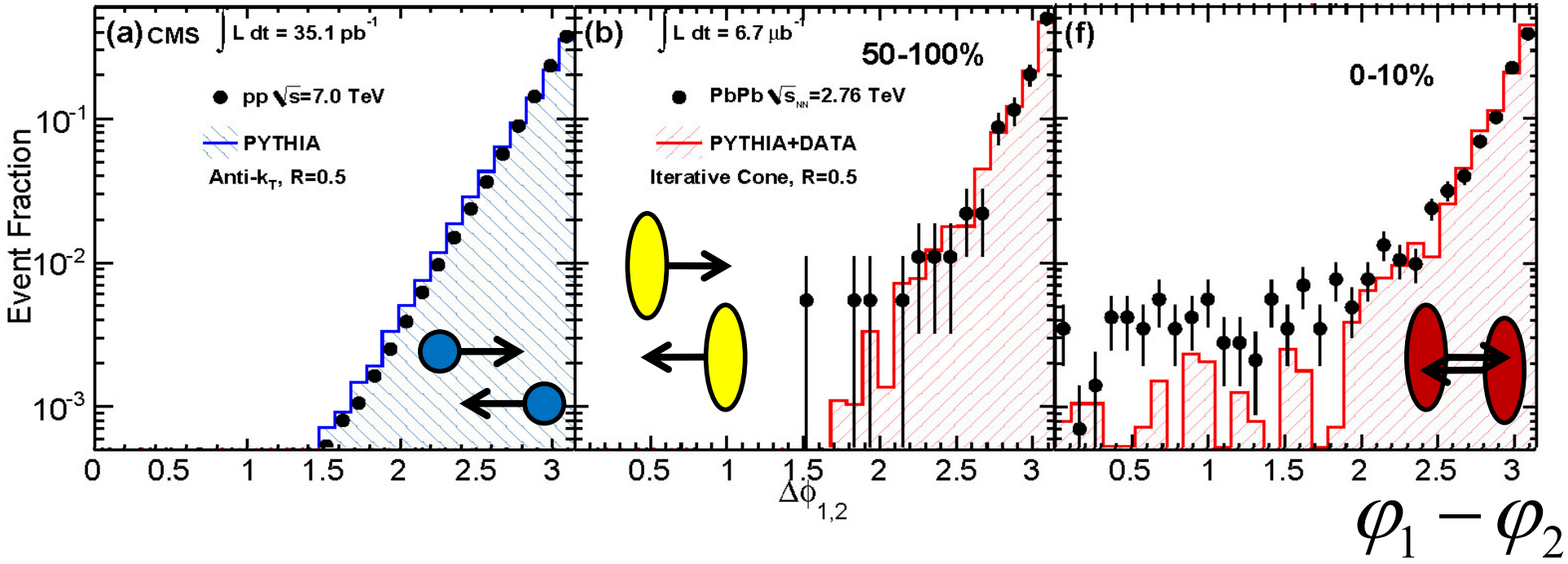
Angular Correlations with jet-jet Measurements…

- The leading jet of $E_T^1 > 120$ GeV and the
- sub-leading jet $E_T^2 > 50$ GeV

stay essentially back-to back ($\Delta\varphi = \pi$)



CMS, PRC84 (2011) 024906



Angular correlations of jets is unmodified by the medium

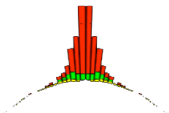
Quantifying Di-jet Measurements

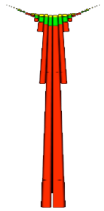
Use Asymmetry ratio :

$$A_j = \frac{E_T^{j1} - E_T^{j2}}{E_T^{j1} + E_T^{j2}}$$

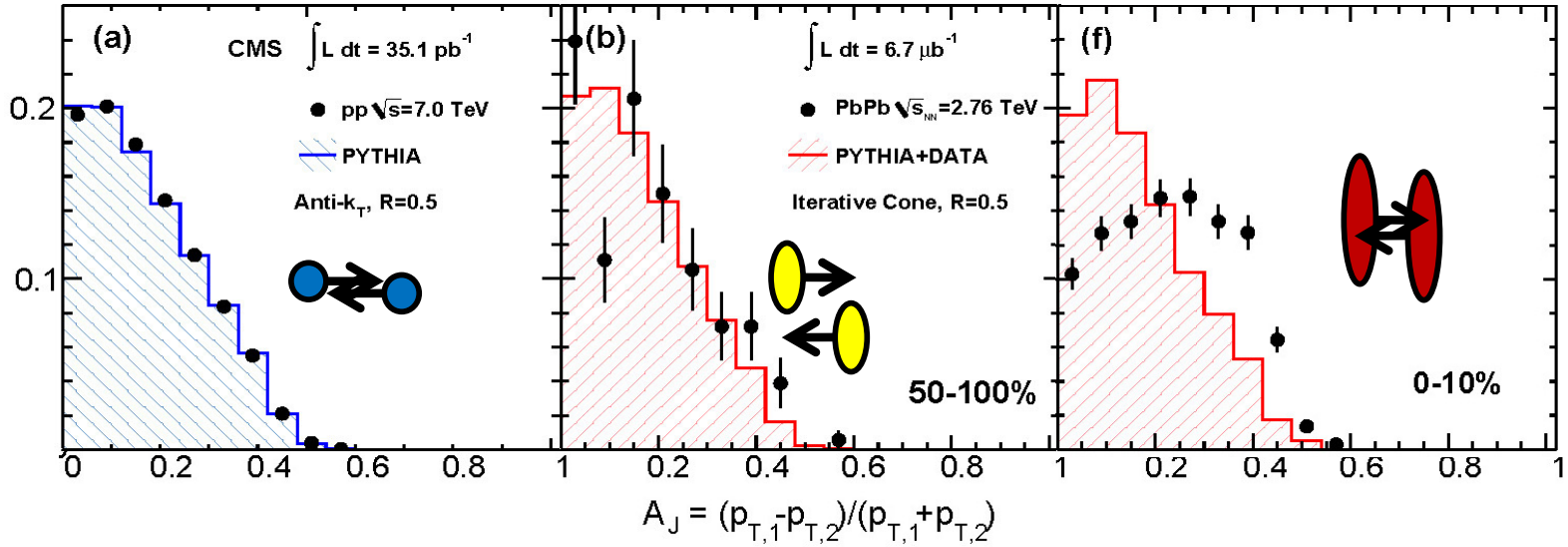
Energy imbalance increases with centrality!

E_T^2



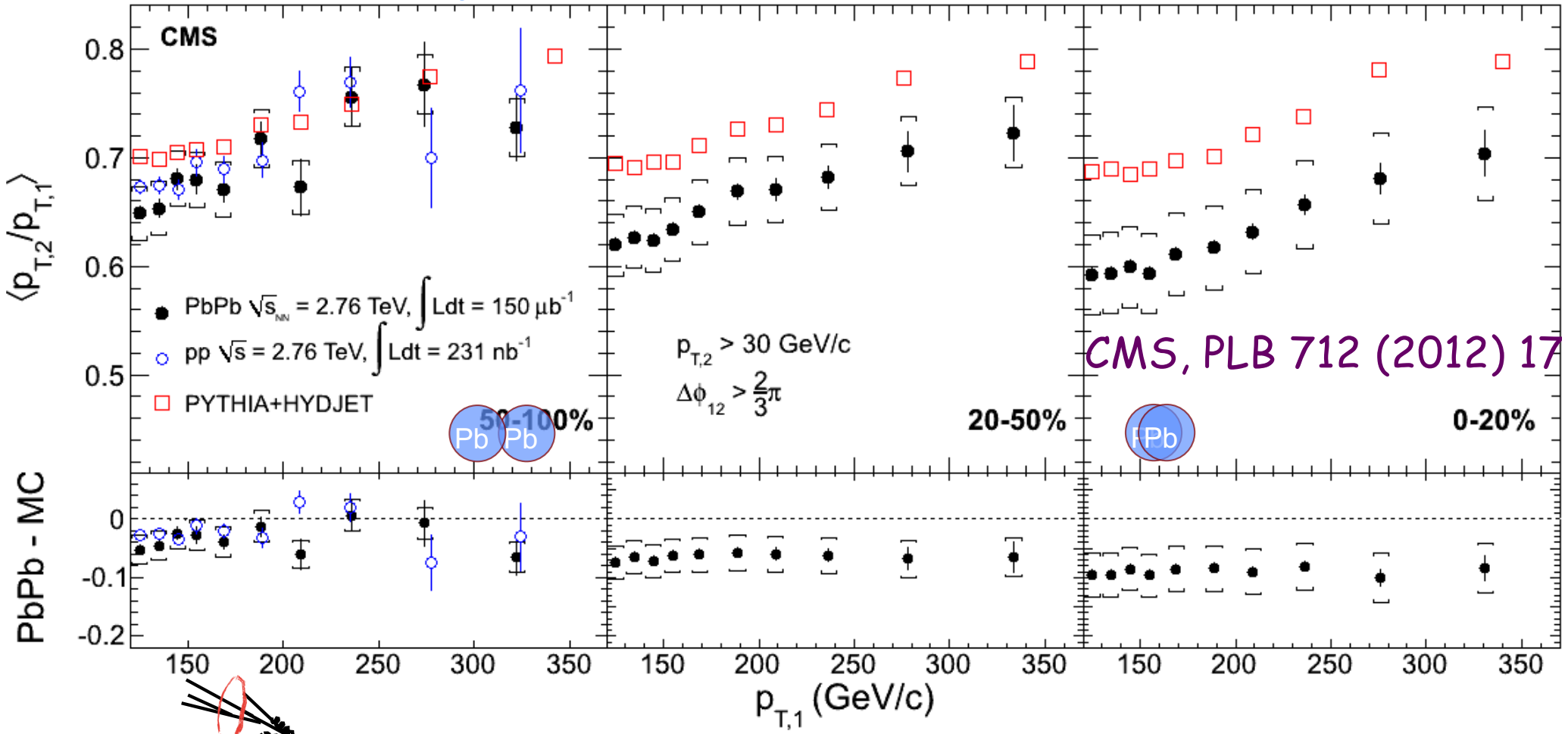


E_T^1

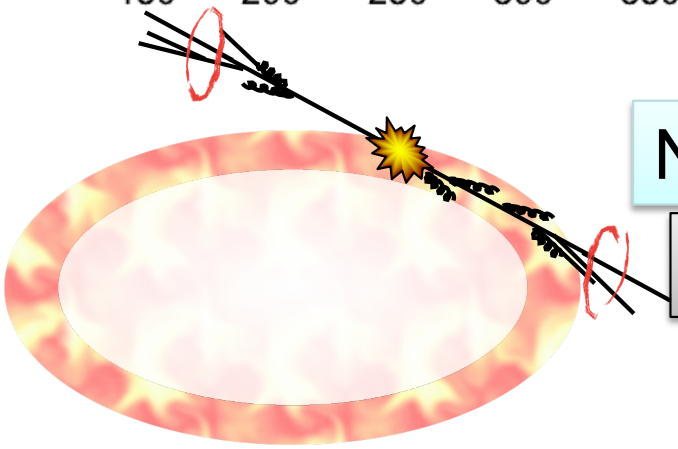


CMS, PRC84 (2011) 024906

The p_T-dependence of jet quenching:



CMS, PLB 712 (2012) 17



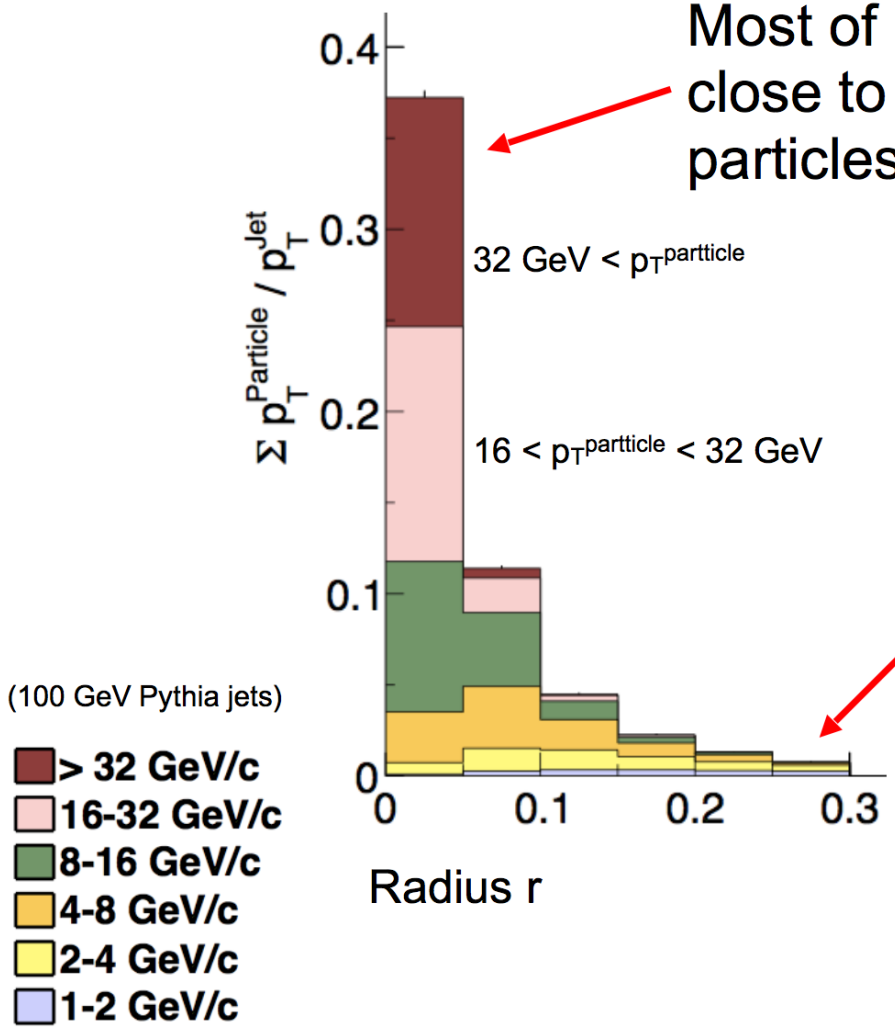
No significant dependence on leading jet p_T

High p_T jets are also quenched!

Loss of information about the initial properties & surface bias.

Jet Morphology:

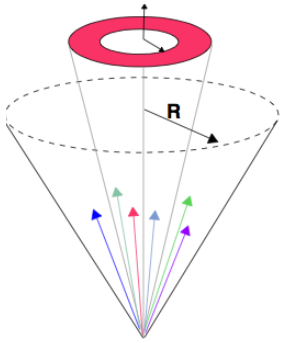
Angular and Momentum Structures



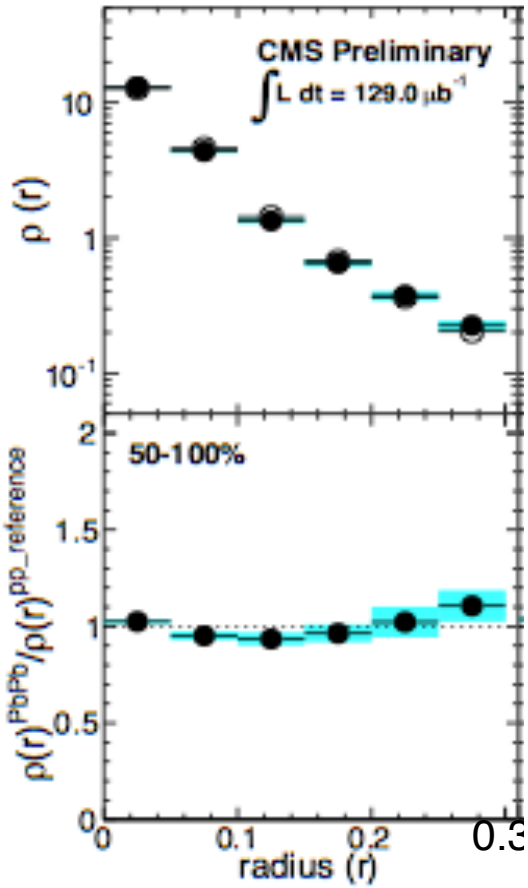
Most of momentum found close to jet axis in high p_T particles (p_T > O(10GeV))

Large angle component of jet contains small fraction of jet p_T in soft particles (p_T ~ O(GeV))

Jet structures: Jet Shapes



CMS, Phys. Lett. B 730 (2014) 243

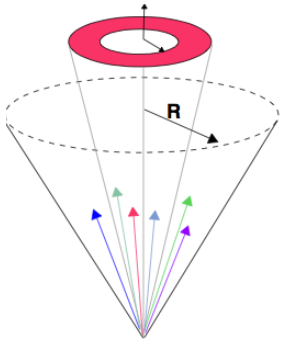


How is the jet energy in PbPb redistributed in radius ?
Differential jet-shapes

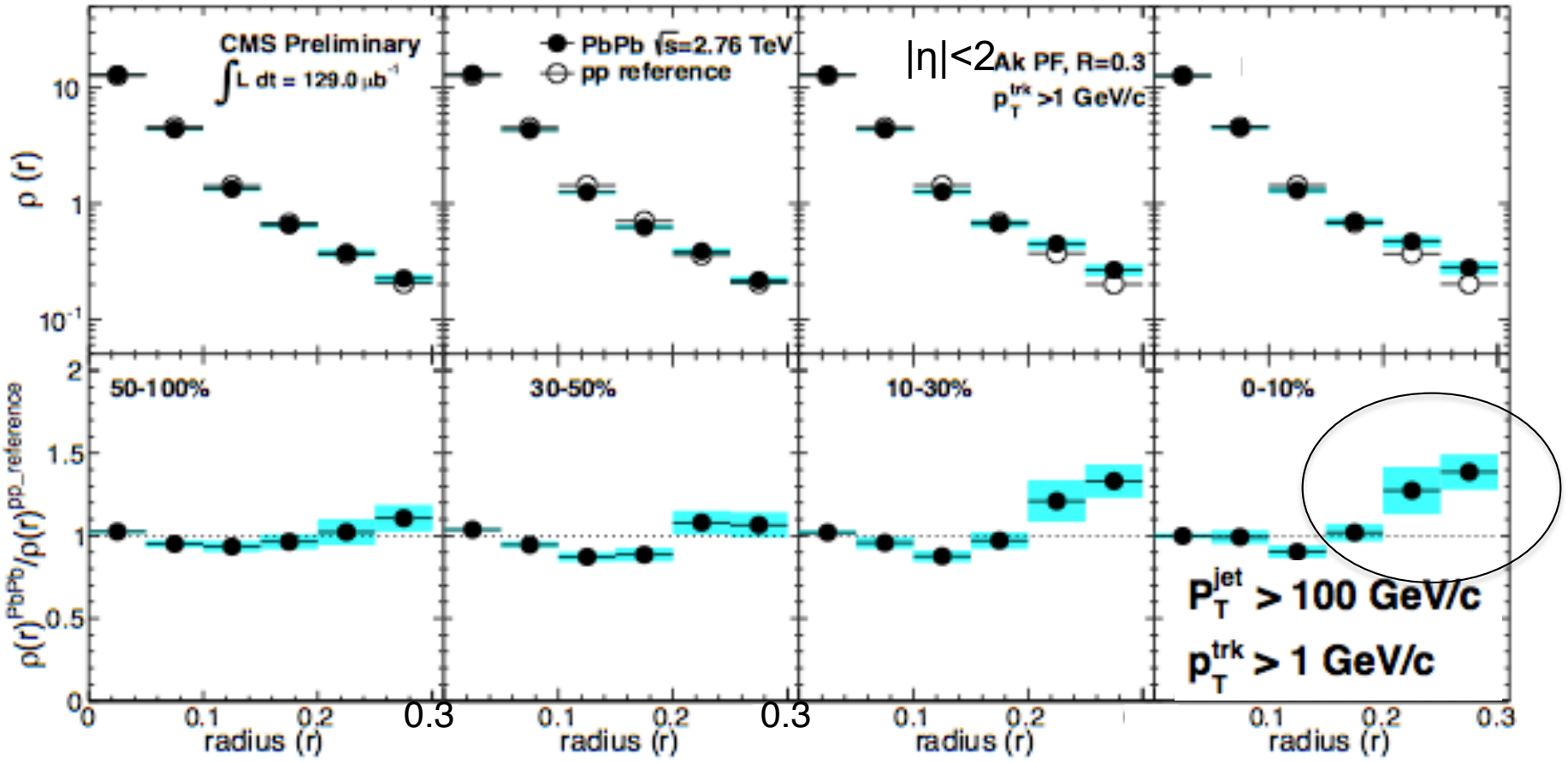
$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jets}}\frac{p_{\text{T}}(r-\delta r/2, r+\delta r/2)}{p_{\text{T}}^{\text{jet}}}$$

p_T fraction inside a given radial annulus in η-ϕ space

Jet structures: Jet Shapes



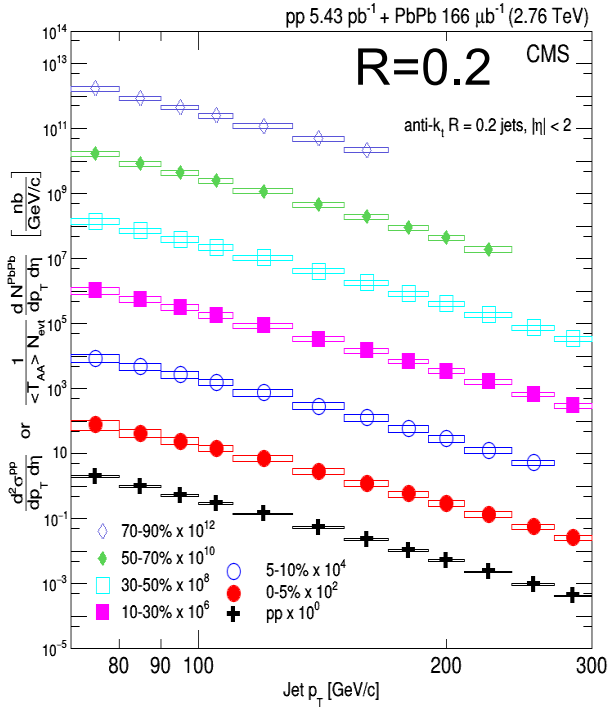
CMS, Phys. Lett. B 730 (2014) 243

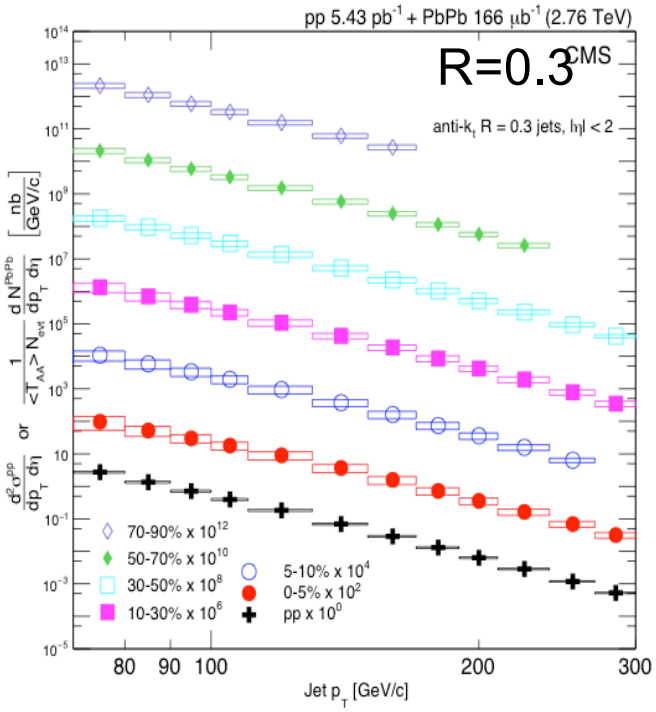


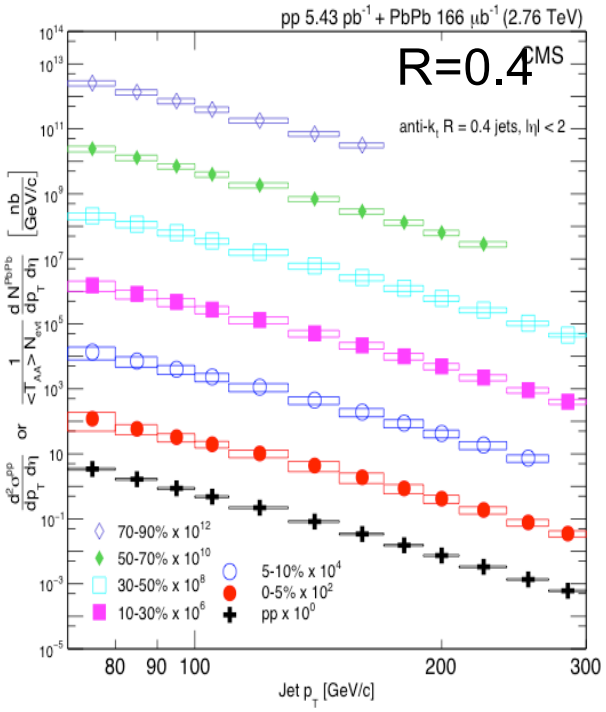
Angular structure of reconstructed jets is modified towards an excess of particles far from the jet axis!

Inclusive Jet Measurements

Cross-section





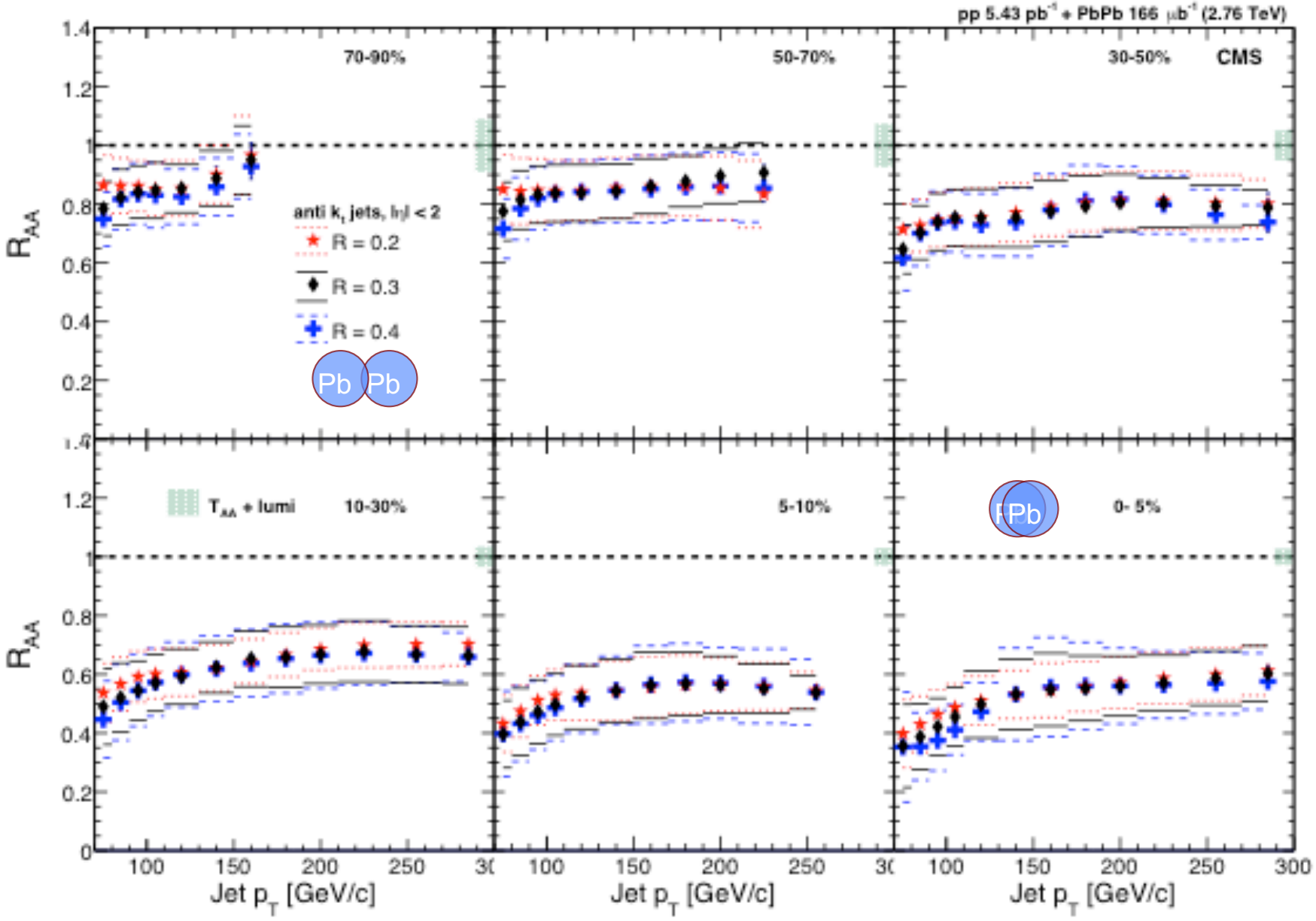


Jet p_T [Gev/c]

CMS, arXiv:1609.05383

Increased low p_T coverage. And 3 different resolution parameters.
Various PbPb centralities & reference pp measurement!

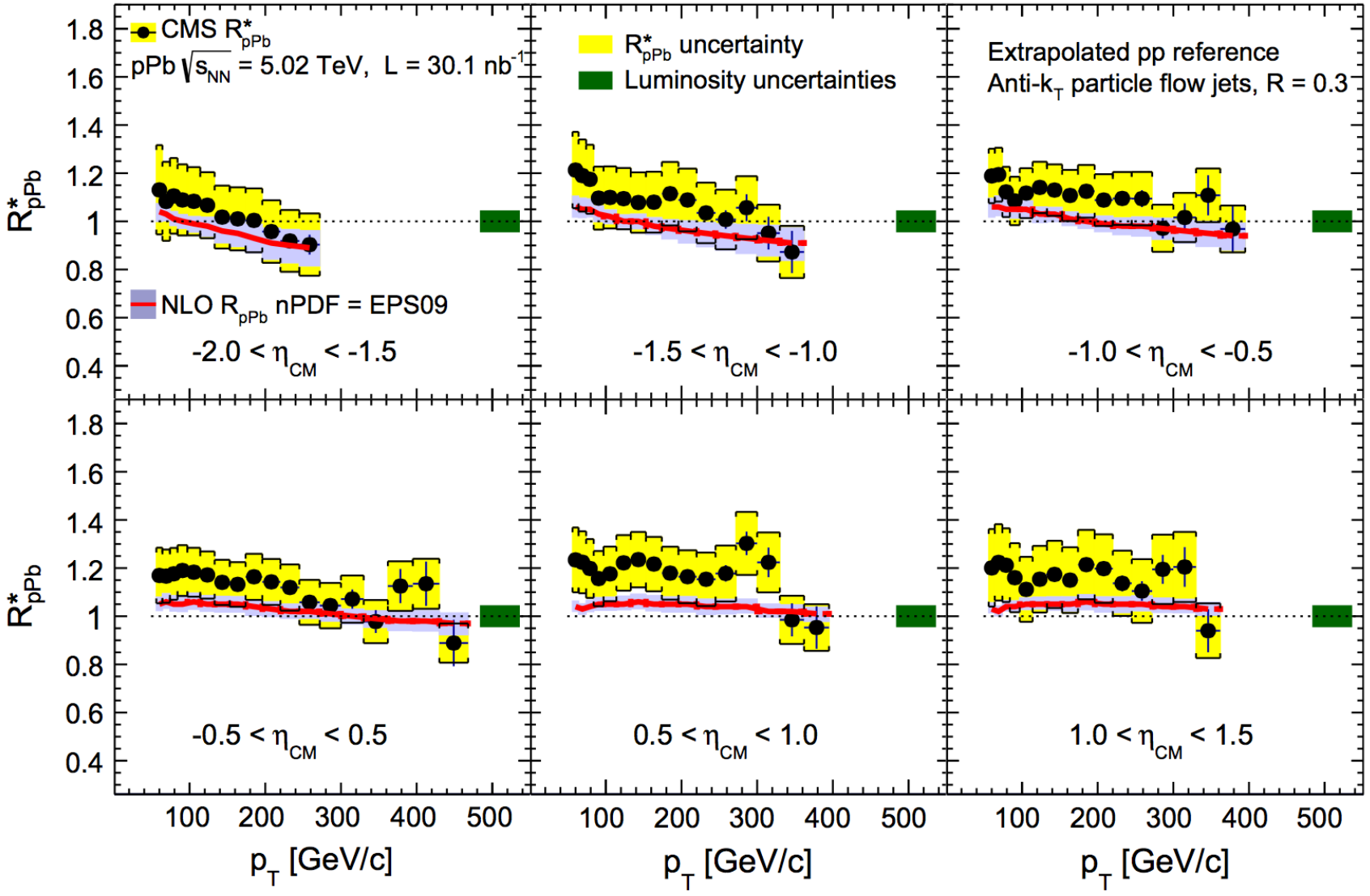
Inclusive Jet R_{AA}: Resolution parameter dependence



No strong dependence on jet radius!

CMS, arXiv:1609.05383

Cold-nuclear matter effects via a study in pPb:



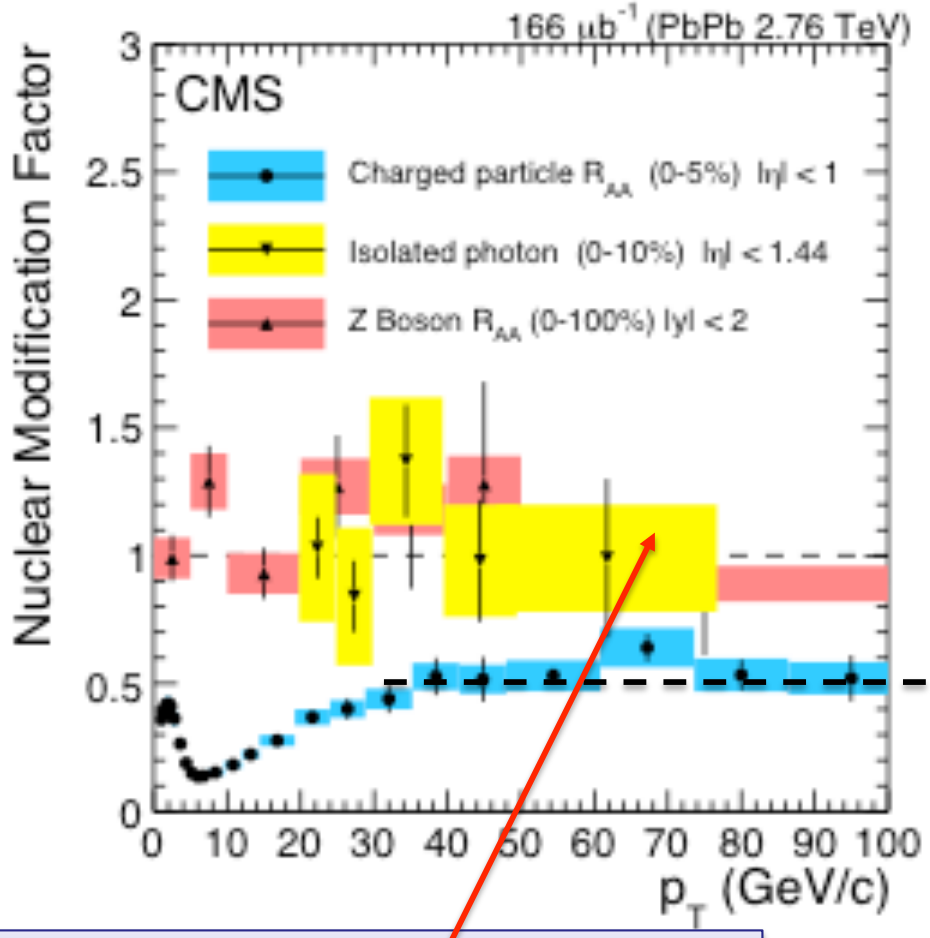
Suppression cannot be explained by nuclear effects!
Systematic enhancement in pPb is under investigation.

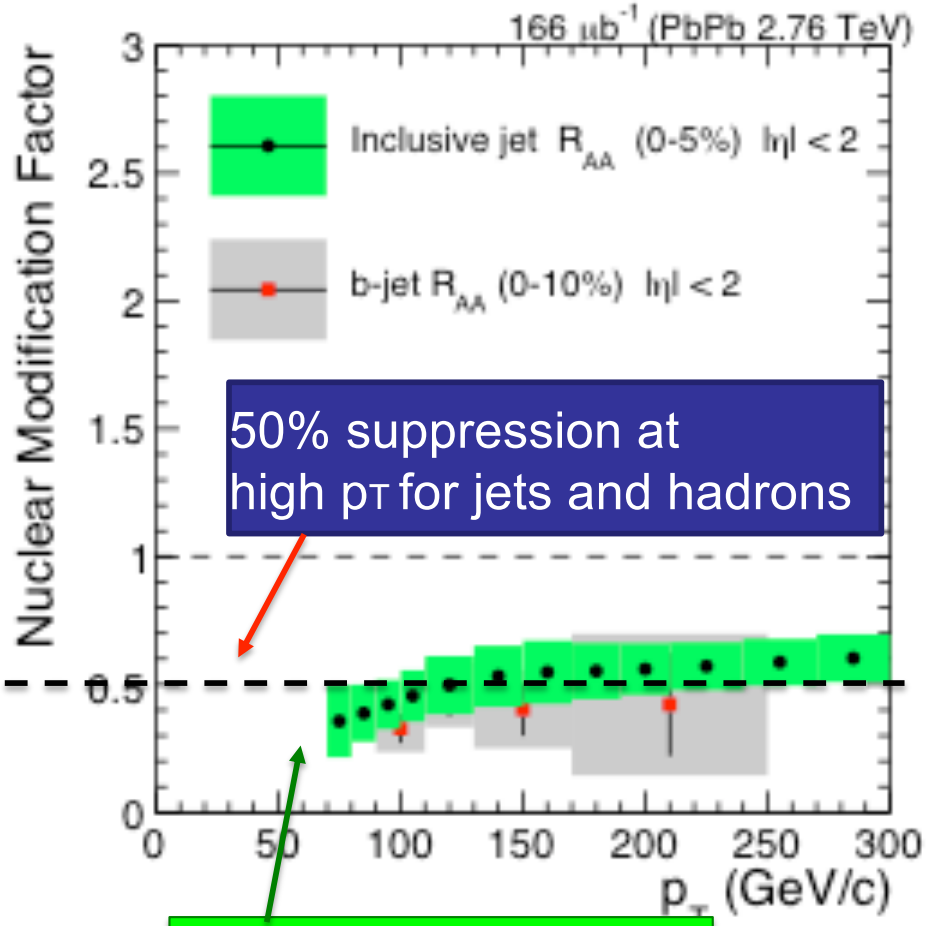
CMS, Eur. Phys. J. C 76, no. 7, 372 (2016)

Quenching summarized…

Particles

Jets





50% suppression at high p_T for jets and hadrons

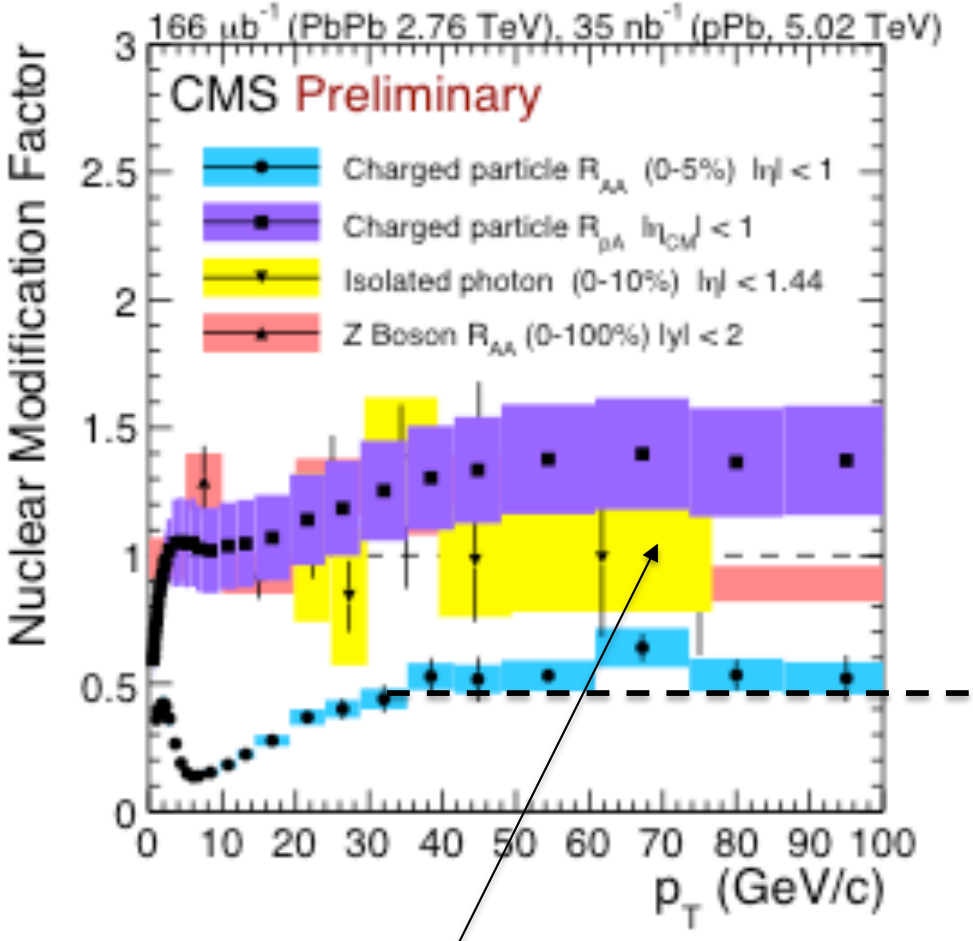
Colorless probes are not modified
N_{coll} scaling works

No flavor/mass dependence at high p_T

$$R_{AA} = \frac{dN^{AA}/dp_T}{\langle T_{AA}\rangle\, d\sigma^{pp}/dp_T} \qquad \langle T_{AA}\rangle = \frac{\langle N_{coll}\rangle}{\sigma^{NN}_{inel}}$$

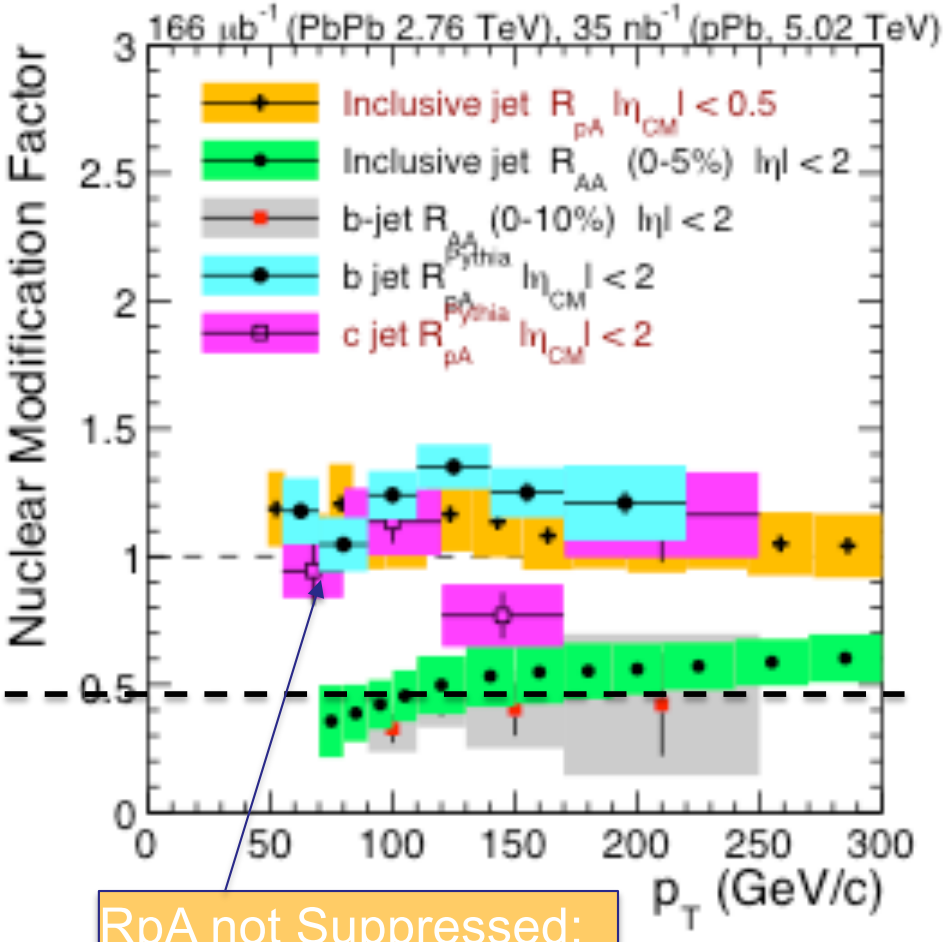
Quenching summarized… Inclusion of RpPb!

Particles



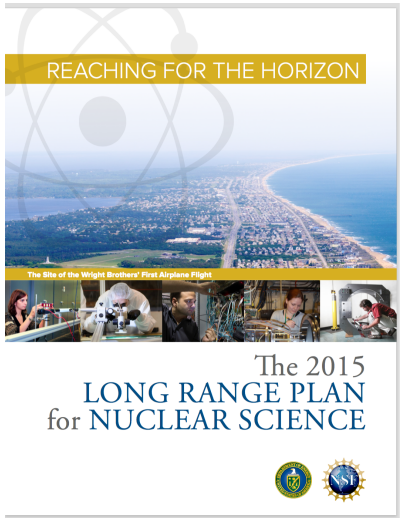
RpA not Suppressed!

Jets



RpA not Suppressed: No flavor/mass dependence at high p_T

Quenching is not due to cold nuclear matter effects but due to strongly interacting medium!



What about Future:

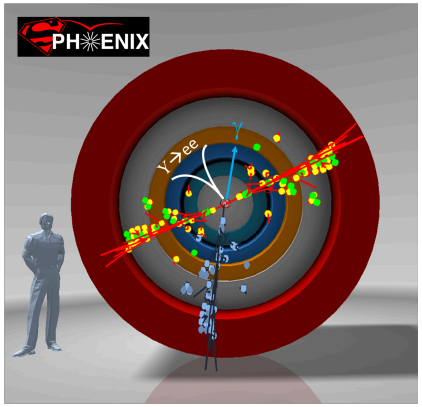
Nuclear Science Long Range Plan

Recommendation 1

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced US world leadership in nuclear science. The highest priority in this 2015 Plan is to **capitalize on the investments made**

- The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton
  - **Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales.** The complementarity of the two facilities is essential to this goal, as is a **state-of-the-art jet detector** at RHIC, called sPHENIX

What about Future:



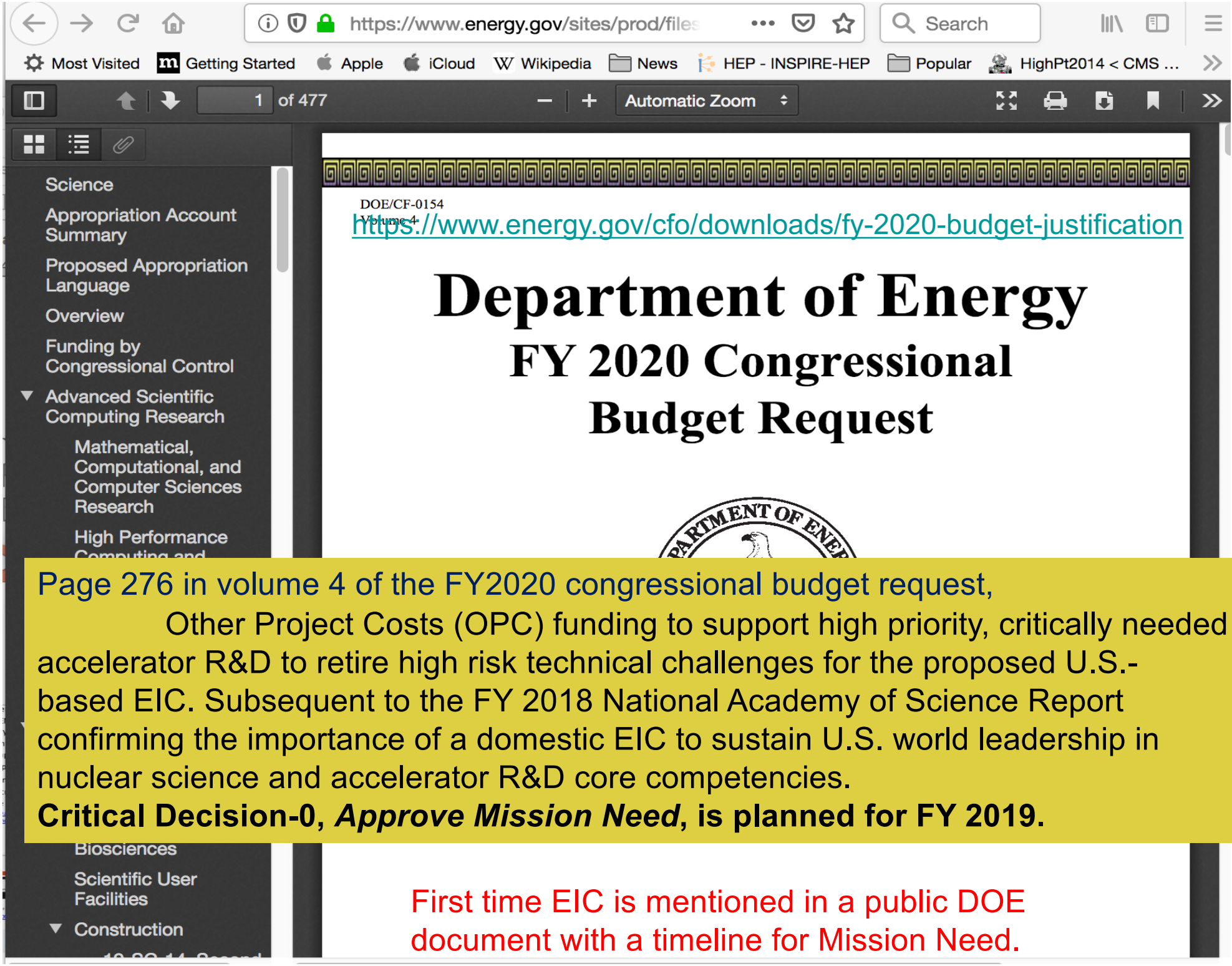
- In order to fully understand the properties of QGP at extreme temperature and density

→ extend LHC/RHIC results

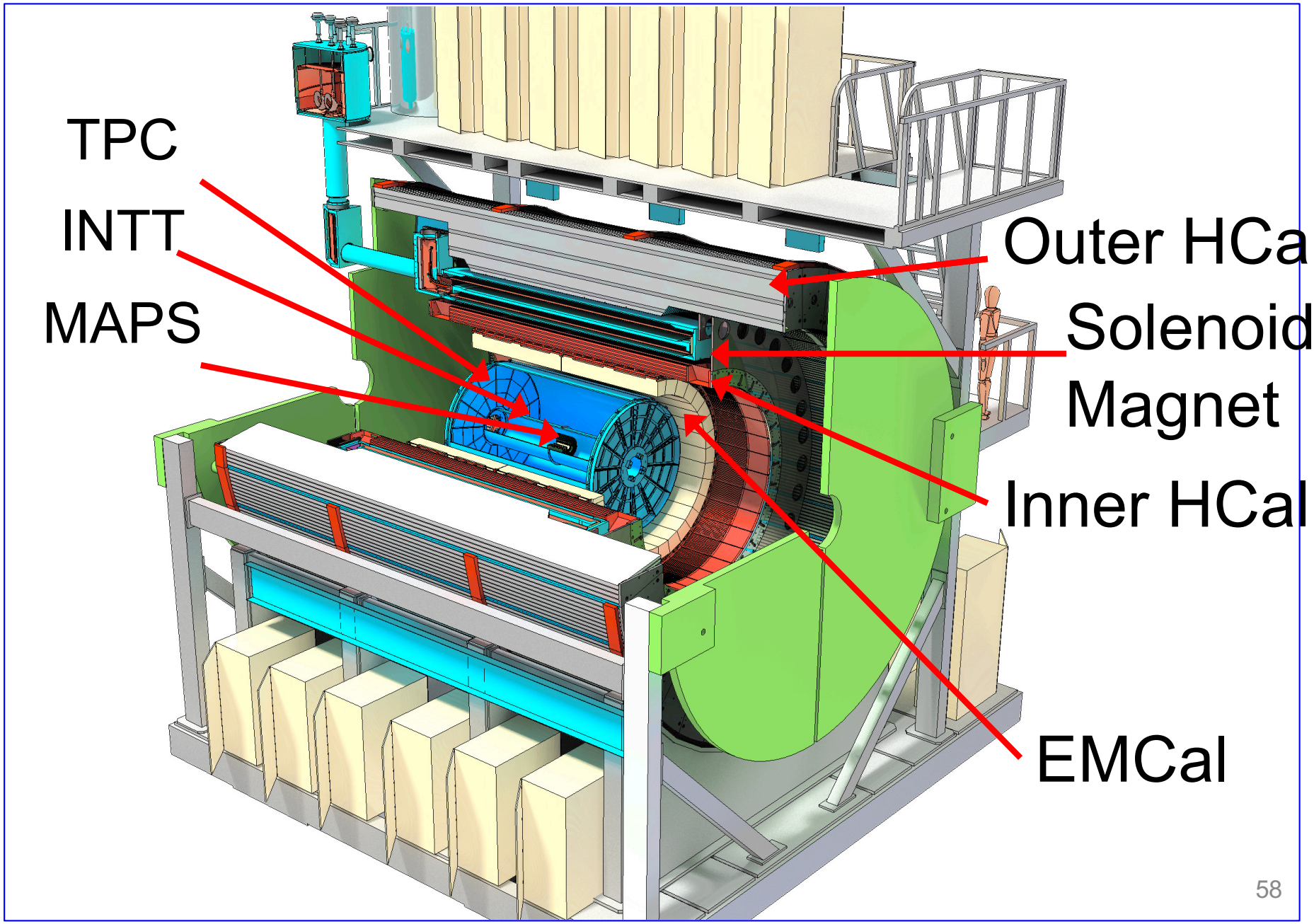
- sPHENIX will allow high statistics measurements for jets, heavy flavour and quarkonia at 200 GeV
- Scientific case for sPHENIX has been demonstrated
  - Supported by the DOE and the community
- The plan is to be **ready for beam January 2023**
- Potential future application as a foundation for an **Electron Ion Collider (EIC)** detector – (Also in the LRNP 2015)
- **BNL** is recently chosen as the **EIC** site**.**
- More information:

http://www.phenix.bnl.gov/phenix/WWW/publish/documents/sPHENIX_proposal_19112014.pdf

Inaugural Collaboration Meeting Held at Rutgers Dec 2015


https://www.energy.gov/sites/prod/files
Search
Most Visited
Getting Started
Apple
iCloud
Wikipedia
News
HEP - INSPIRE-HEP
Popular
HighPt2014 < CMS ...
1
of 477
Automatic Zoom
Science
Appropriation Account Summary
Proposed Appropriation Language
Overview
Funding by Congressional Control
Advanced Scientific Computing Research
Mathematical, Computational, and Computer Sciences Research
High Performance
Biosciences
Scientific User Facilities
Construction
DOE/CF-0154
Volume 4
https://www.energy.gov/cfo/downloads/fy-2020-budget-justification
Department of Energy
FY 2020 Congressional
Budget Request
Page 276 in volume 4 of the FY2020 congressional budget request,
Other Project Costs (OPC) funding to support high priority, critically needed accelerator R&D to retire high risk technical challenges for the proposed U.S.-based EIC. Subsequent to the FY 2018 National Academy of Science Report confirming the importance of a domestic EIC to sustain U.S. world leadership in nuclear science and accelerator R&D core competencies.
Critical Decision-0, Approve Mission Need, is planned for FY 2019.
First time EIC is mentioned in a public DOE document with a timeline for Mission Need.

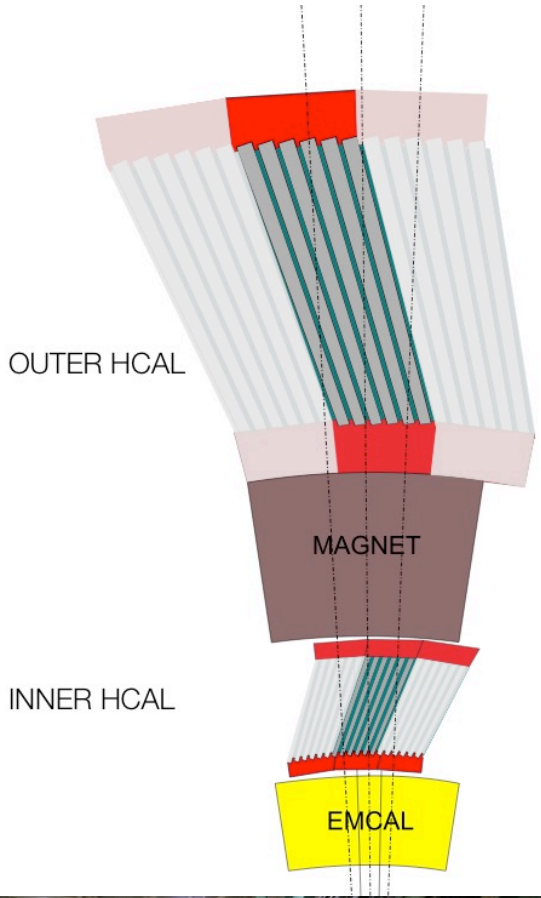
The sPHENIX Detector



Importance of Calorimetry

- Measure Jet energy
- Identify photons and electrons

Physics Goal	Detector Requirement
Jets/Fragmentation Functions/jet substructure	Single particle Resolution: $\sigma/E < 100\%/\sqrt{E}$
Distinguish Upsilon States	Good e/π separation
HF jet tagging	Electron ID



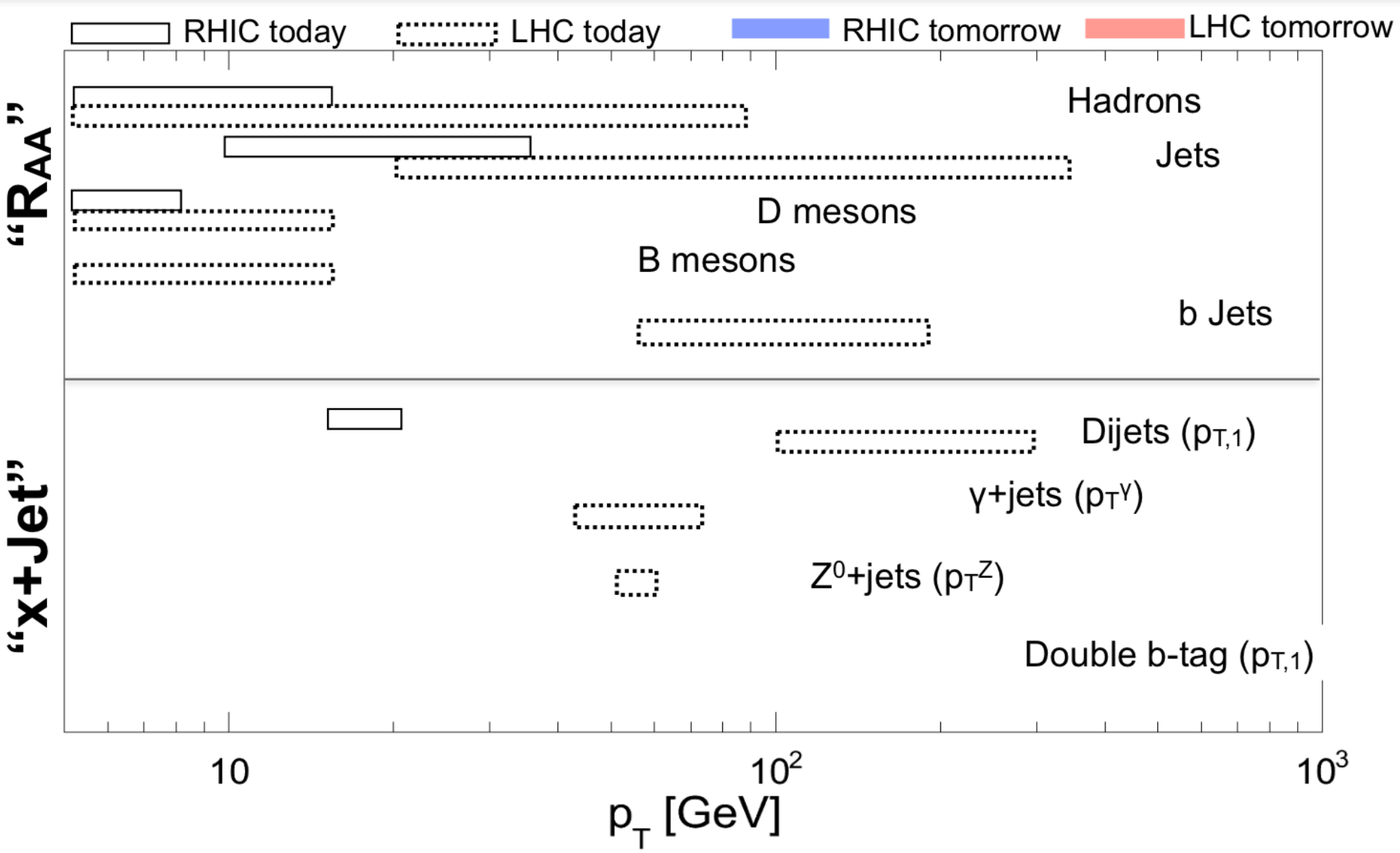
EMCal Towers: fibers embedded in Tungsten-epoxy

HCal: Plastic scintillator tiles with embedded fiber between tilted steel plates

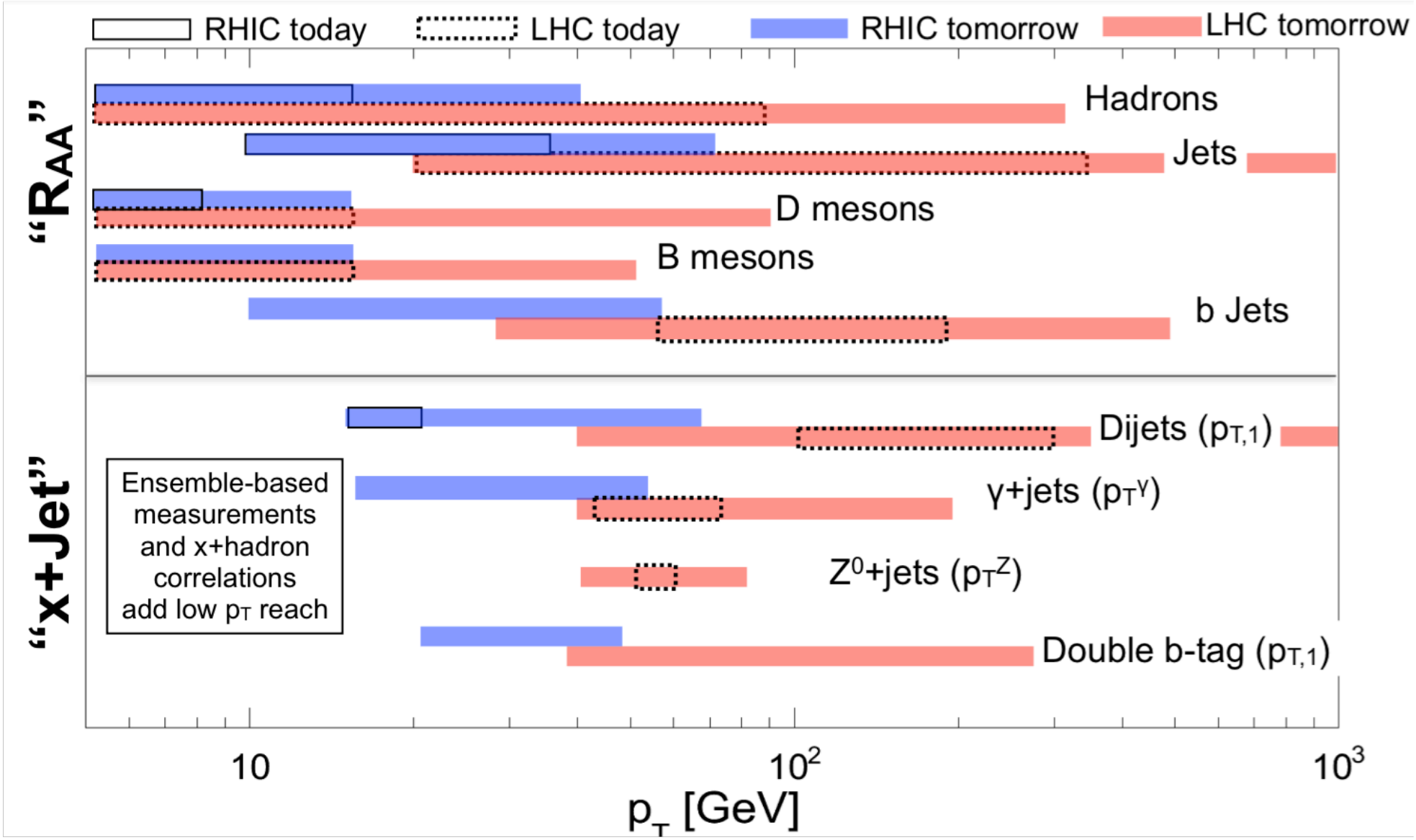
At Rutgers, machining of plates & assembly of hcal sectors.

Sevil Sa

What about Future:



What about Future:



- Larger p_T coverage with smaller uncertainties
- RHIC/LHC overlap

Are we there yet?

Jet Tomography has been explored with multiple jet observables.

pp reference at 5 TeV is already collected.

- Detailed studies of jets for initial state effects with pp reference will be soon available for inclusive jets, γ+jet, c/b+jet but also for Z+Jet, additional tags with B/D …

Improvement in jet statistics in PbPb and AuAu.

- Explore underlying partons properties with reconstructed jets.
- Event plane dependent Jet Tomography with: Jet shapes, FF, sub-structure for a complete characterization of final state

Tune QCD Temperature with RHIC & LHC!

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Tune QCD Temperature with RHIC & LHC!

This represents significant progress in our understanding of the strong nuclear force

We now need to show its properties **quantitatively !**